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THE JOURNAL OF THE ROYAL AERONAUTICAL SOCIETY

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LONDON
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Secretary's News Letter

FEBRUARY 1952

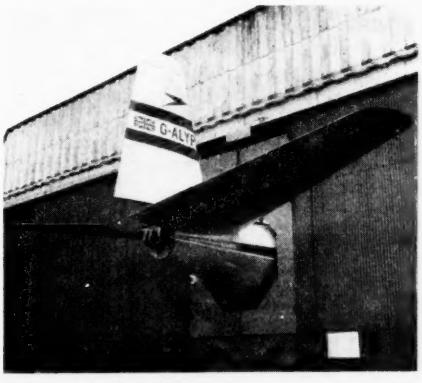
AS I write the New Year is fifteen days old; it will be older when this is read, but nevertheless I wish to send my belated thanks to all who sent Christmas Cards to the Society's staff, and to send them our best wishes for 1952.

From the January issue the Secretary's News Letter and the Notices have been incorporated in the JOURNAL. These are placed at the beginning, and at the end, in the Review Section, will be found "Additions to the Library." As previously there is a separate printing of the News Letter and Notices, which is sent to those who do not take the JOURNAL.

Another innovation is the Diary of Lectures. All the Branch meetings for the Spring Session which had been received from the Branches, were published in the December Notices, but as from January the meetings are given in the form of a Diary from the 15th of one month to about the 20th of the next. For this diary to be complete we must have the co-operation of *all* the Branches; it will be seen that there are a few Branches whose meetings are not listed. I hope that those Branches will let the Editor have a list of their meetings in time for the March JOURNAL, not later than the 19th February.

On the 28th December 1951 the Weybridge Branch held their Annual Dance, which at the invitation of the Chairman, Mr. H. H. Gardner, and his Committee, Miss Barwood and I attended. It was a very good dance; the Branch Secretary, Mr. J. H. Sinclair, is to be congratulated on its success. The Master of Ceremonies, complete in red coat, added to the joy of the evening with his imaginative renderings of the usual and unusual ballroom novelties. I was surprised at the reception given to the "Gay Gordons" to the tune of "The Cock o' the North." I wonder how long it will take Mr. Sinclair to make popular the even more strenuous eightsome reel? I am assured that the reel will be on the programme in December 1952.

I spent an interesting afternoon with Mr. F. E. N. St. Barbe at de Havilland's, Hatfield. The original offices of the Company, a small wooden hut at Stag Lane, have been removed to Hatfield. The motto of the Aircraft Industry, judging from the smallness of the hut, could be said to be: "Quondam multum in parvo, nunc in multo multum"—which might be freely translated as: "Look at us now."



I was shown round the Comet assembly shop by Mr. St. Barbe, and during my tour I saw the Comet with its tail through the wall. It seemed to me rather bizarre, and I begged the photograph which appears alongside. "Cribbed, cabined but unconfined." I had the feeling that the hat should be raised on passing.

During the month I have had a visit from Mr. M. S. Kuhring, of the National Research Council of Canada, who is head of the Engine Laboratory. He is in this country for a conference, but he hopes to find time to meet some old friends.

This year the Garden Party will be in June, after Major Halford's term of office as President will have finished. He has proposed that a Buffet Dance be held and the tentative arrangements are to hold this function at the Dorchester on Saturday 3rd of May 1952. It is estimated that the cost of the tickets will be 30s. single and £3 double. In order that the final arrangements can be made it would be of great assistance if members who wish to attend the dance would let me know as soon as possible.

Secretary

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CONTENTS OF THE FEBRUARY JOURNAL

Modern Trends in Civil Airworthiness Requirements, W. Tye, O.B.E., F.R.Ae.S.

A Shortened Method for the Calculation of Aerofoil Profile Drag, E. M. Dowlen, D.L.C., D.C.Ae., Grad.R.Ae.S.

The Technique of Resonance Testing and Flutter Calculations as Applied to Fighter Aircraft Design, C. P. Plantin, B.Sc., A.F.R.Ae.S.

Reviews. Correspondence.

(An annual sum of £250 is available for premium awards for papers published in the Journal. These premium awards average 15 guineas each. Members and non-members of the Society are invited to submit papers on any aspect of aeronautics.)

THE AERONAUTICAL QUARTERLY—Part III, Volume III

Part III, November 1951 of the Aeronautical Quarterly is still available. The Contents of Part III, Volume III are:—

Photoelasticity and Aircraft Design	H. T. Jessop and C. Snell
A Note on the Design of Ducted Fans	B. Thwaites
A New Treatment of the Tuned Absorber with Damping ...	D. C. Johnson
A New Approach to Thin Aerofoil Theory	M. J. Lighthill
The Profile Drag of Yawed Wings of Infinite Span ...	A. D. Young and T. B. Booth
Beams on Cross-Girders with Clamped Ends	J. M. Klitchieff
A Direct Aerodynamic Proof of the Biot-Savart Law ...	J. Lockwood Taylor

Copies of Volume III, Parts I and II, are still available from the offices of the Society at 7s. 9d. a copy to members of the Society, post paid, or 10s. 3d. to non-members, post paid.

NEW YEAR'S HONOURS LIST 1952

The following members were included in the New Year's Honours List:—

K.B

Professor L. Bairstow (*Honorary Fellow*)
D. R. Pye (*Fellow*)

K.C.B.E.

Acting Air Marshal C. W. Weedon (*Associate Fellow*)

C.B.E.

Acting Air Commodore C. L. Dann (*Associate Fellow*)
Group Captain J. M. Freeman (*Associate*)
H. L. Stevens (*Fellow*)

O.B.E.

Wing Commander G. L. Gandy (*Associate*)

M.B.E.

J. H. Hamilton (*Graduate*)

King's Commendation for Valuable Service in the Air

Squadron Leader K. Ritchley (*Associate Fellow*)

NOMINATION OF CANDIDATES FOR COUNCIL

The following is an extract from the By-laws:—

"The Twenty-one ordinary members (of the Council) shall be nominated and elected from among the members of the Society. At the date of their election at least ten shall be Fellows, and one at least shall be in each of the following classes: Associate Fellow, Associate and Graduate.

"Of the ordinary members of the Council, that number necessary to create seven vacancies shall retire annually. The retiring members shall be those with the longest service since their last election but they shall be eligible for re-election.

"Nominations of candidates for election to the Council must be received by the Secretary not later than 10th April in each year and shall include statements in writing by the candidates that they are willing to serve. The nomination forms shall be signed by one proposer and two seconders, all of whom shall be Voters."

Nomination forms may be obtained on application to the Secretary.

ELECTION OF FELLOWS

The attention of members is drawn to the following extract from the By-laws:—

"Elections to Fellowship will be made annually by the Council and will be announced at the Annual General Meeting of the Society. Nominations will be initiated by the members of the Council or by any four Fellows of the Society. It is the duty of the Council to see that the honour is awarded only to persons who have attained a considerable degree of technical eminence in the profession of aeronautics."

Nominations initiated by any four Fellows of the Society should be received by the Secretary on or before 15th April 1952 to give sufficient time for the Council to consider them in time for announcement at the Annual General Meeting in May.

MEMBERS' NEW APPOINTMENTS

MR. E. H. ATKIN (*Fellow*) has recently been appointed to the newly created position of Technical Director of A. V. Roe Canada, Ltd. He was formerly Chief Engineer.

WING COMMANDER E. H. COLEMAN (*Associate Fellow*) has been appointed Director of Civil Aviation, West Africa. He was formerly Director of Civil Aviation, Bahamas.

MR. JAMES C. FLOYD (*Associate Fellow*) has been appointed Chief Engineer, A. V. Roe Canada, Ltd. He was formerly Works Manager.

MR. A. A. LOMBARD (*Associate Fellow*) has been appointed Chief Designer of the Aeronautical Division of Rolls-Royce Limited.

MR. L. MASSEY HILTON (*Associate Fellow*) has been appointed an additional Assistant Managing Director of the Fairey Aviation Co. Ltd. He has been a Director of the Company since 1934.

MR. F. H. POLLICUTT (*Fellow*) has been appointed Chief Designer of Folland Aircraft Ltd. He was formerly Deputy Chief Designer with the Bristol Aeroplane Co. Ltd.

MR. A. A. RUBBRA (*Fellow*) has been promoted to Deputy Chief Engineer of the Aeronautical Division of Rolls-Royce Limited. He has been with the Company since 1925.

MR. W. A. TAMBLIN (*Associate Fellow*) has been appointed to take charge of the Airspeed Division Design and Experimental Departments of the de Havilland Aircraft Co. Ltd. at Christchurch, Hants.

FIFTH LOUIS BLERIOT LECTURE, PARIS 1952

The Fifth Louis Bleriot Lecture will be given by H. Knowler, A.M.I.C.E., F.R.Ae.S., Director and Chief Designer, Saunders-Roe Ltd. The Lecture, on "The Future of the Flying Boat," will be given on 12th March 1952 at the Société des Anciens Elèves Ingénieurs Arts and Métiers, 9b Avenue d'Iena, Paris XVI^{e} at 5.30 p.m. A cocktail party will follow to which all British visitors to the lecture are invited. There will also be an official dinner at the Aero Club de France but those wishing to attend the dinner should let the Secretary of the Society at 4 Hamilton Place know immediately so that invitations may be sent to them.

FORTIETH WILBUR WRIGHT MEMORIAL LECTURE 1952

The Fortieth Wilbur Wright Memorial Lecture will be given by Sir Harry M. Garner, C.B., M.A., F.R.Ae.S., Chief Scientist to the Ministry of Supply, on 29th May 1952, on "Prophecy and Achievement in Aeronautics." The Lecture will be held at the Institution of Civil Engineers, Great George Street, S.W.1, at 6 p.m.

DIARY

LONDON.

February 19th

SECTION LECTURE—Recent Development in Glider Design. K. G. Wilkinson. 4 Hamilton Place, W.I. 7 p.m.

February 26th

GRADUATES AND STUDENTS SECTION—Sailplanes and Meteorology:- Meteorology from the Pilots' Point of View. L. Welch and Gravity as an Aid to Soaring. R. S. Scorer. 4 Hamilton Place, W.I. 7.30 p.m.

March 4th

SECTION LECTURE—Bogie Undercarriages. R. C. Cussons. 4 Hamilton Place, W.I. 7 p.m.

March 6th

MAIN LECTURE—A Study of Airport Noise. J. D. Hayhurst. Institution of Civil Engineers, Great George Street, W.I. 6 p.m. (Tea at 5.30 p.m.).

March 11th

GRADUATES AND STUDENTS SECTION—An Introduction to Supersonics, C. H. E. Warren. 4 Hamilton Place, W.1. 7.30 p.m.

SPECIAL LECTURES.

February 21st

MAIN SOCIETY LECTURE AT HULL—Power Steering for Aircraft, K. G. Hancock and P. Person.

March 12th

FIFTH LOUIS BLERIOT LECTURE, PARIS—The Future of the Flying Boat. H. Knowler.

BRANCHES.

February 19th
Belfast—Modern Aircraft Manufacturing Processes and Techniques, F. H. Parker. College of Technology. 7 p.m.

February 20th
Coventry—Parachutes, J. E. Hatfield. The Wine Lodge. 7.30 p.m.
Southampton—An Introduction to Supersonics, C H. E. Warren. University College. 7 p.m.
Weybridge—Flight Testing from the Pilot's Angle, Wing Commander T. Balmforth, D.S.O., D.F.C. Vickers-Armstrongs Ltd. 6 p.m.

February 21st
Brough—Main Society Lecture. Power Steering for Aircraft, K. G. Hancock and P. Person. Electricity Showrooms, Hull. 7.30 p.m.

February 25th
Halton—FILMS. Halton Camp. 6.45 p.m.
Yeovil—The Giant Helicopter, O. O. Fitzwilliams. The Park School. 7.30 p.m.

February 26th
Bristol—The Campaign Against Terrorism in Malaya, Air Vice-Marshal Sir Francis J. W. Mellersh, K.B.E., A.F.C. Filton House. 6 p.m.

February 27th
Hatfield—Airships, Lord Ventry. de Havilland Aircraft Co. Ltd. 6.15 p.m.

February 28th
Gloucester and Cheltenham—The Development of the Aircraft Gas Turbine in Great Britain and its Influence on Petroleum Requirements, K. C. Hunt. St. Mary's College, Cheltenham. 7.30 p.m.
Isle of Wight—Radio and Radar Navigational Aids, H. C. Hinckley. Saunders-Roe Club House, E. Cowes. 6 p.m.
Portsmouth— Rocket Propulsion—the Prospects for Inter-Planetary Flight, J. Humphries. Airspeed Ltd. 6 p.m.

March 3rd
Derby—Present and Future Trends in Air Line Operation, H. W. Seagrim. Rolls-Royce Welfare Hall. 6.15 p.m.
Halton—Flight Refuelling, C. H. Latimer-Needham. Halton Camp. 6.45 p.m.

March 4th
Chester—Synthetic Adhesives. Grosvenor Hotel. 7.30 p.m.

March 10th
Halton—FILMS. Halton Camp. 6.45 p.m.

March 12th
Hatfield—Comet Operation, Captain Majendie. de Havilland Aircraft Co. Ltd. 6.15 p.m.
Weybridge—Planning and Aircraft Development, F. Olaf Thornton. Vickers-Armstrongs Ltd. 6 p.m.

March 13th
Isle of Wight—The Princess, H. Knowler. Saunders-Roe Club House, E Cowes. 6 p.m.
Manchester—The Problems in the Design of Wheels, J. Wright. College of Technology. 7.30 p.m.
Portsmouth—FILMS: Houses in History; Gems of the Rockies: This is Britain: and Turbo Jet Propulsion. Airspeed Ltd. 6 p.m.

March 17th
Halton—Aircraft of World War I. Leading Apprentice D. E. Gibbings. Halton Camp. 6.45 p.m.

March 19th
Brough—Airships, Lord Ventry. Electricity Showrooms, Hull. 7.30 p.m.
Southamptom—Development of the Viscount, G. R. Edwards, M.B.E. University College. 7 p.m.

March 20th
Yeovil—Technical Brains Trust. The Park School. 7.30 p.m.

ROYAL METEOROLOGICAL SOCIETY DISCUSSION

The Royal Meteorological Society will hold a Discussion on "Meteorology and the Operation of Jet Aircraft" on 20th February 1952, from 3 p.m. to 7 p.m., at the Institution of Electrical Engineers, Savoy Place, W.C.2. Members of the Society are cordially invited to attend.

SCHOLARSHIPS AWARDED BY THE SOCIETY

The attention of members is drawn to the following scholarships awarded by the Society:—

The Royal Aeronautical Society Charter Scholarship.—A Scholarship, or Scholarships, up to the value of £300 a year can be awarded and these scholarships, in the first instance, will be awarded for a period of one year, although an extension of the Scholarship for a second year will be looked upon favourably by the Council if it is clear that the student and the work would benefit by such an arrangement.

The Geoffrey de Havilland Memorial Scholarship.—A Scholarship, or Scholarships, up to the value of approximately £120 a year for a period of one year, although an extension of the Scholarship for a second year will be looked upon favourably by the Council if it is clear that the student and the work would benefit by such an arrangement.

The general regulations for both scholarships are as follows:—

The Scholarships shall be awarded annually, or at such other times as may be decided by the Council, to assist a student wishing to undertake advanced work or study in aeronautics.

The Scholarships will be awarded only to those who can satisfy the Council that they have the necessary qualifications to benefit, and whose proposals for work or further studies are acceptable to the Council. Normally, the work should lead to some higher degree or post-graduate diploma, although this is not essential.

The Council will select from the applicants those whom it considers suitable, and will call such applicants for interview in the offices of the Society before such Board as may be decided by the Society.

Students wishing to apply for the Scholarships should write to the Secretary of the Society not later than 1st June, stating the course they intend to follow, and giving full particulars of their age and the results of any examinations taken by them.

SOCIETY OF BRITISH AIRCRAFT CONSTRUCTORS EDUCATIONAL GRANTS

A number of Educational Grants are awarded by the Society of British Aircraft Constructors to boys between the ages of 16½ and 18, for the assistance of young men who are unable, for financial reasons, to take up a course of education fitting them to become aircraft engineers.

The value of the scholarship will depend upon the circumstances of the holder. The intention of the Society is to supplement the scholarship holder's means (taking into account the payment made by the employer) up to an amount which, in the opinion of the Selection Committee, will be sufficient to enable the holder to maintain himself during his training.

Application forms may be obtained from the Royal Aeronautical Society, 4 Hamilton Place, London, W.1.

ACKNOWLEDGMENT

The Council acknowledge with grateful thanks the gift of slides and a book from F. W. R. Bird, Esq., *Associate Fellow*, and the return of back numbers of the JOURNAL from G. W. Bone, Esq., *Associate Fellow*, and J. C. Guttridge, Esq., *Associate Fellow*.

ELECTIONS

The following is a list of new members and transfers of membership of the Society:—

Associate Fellows

Ermanno Bazzocchi
Richard George Bassett Burr (*from Graduate*)
David John Caple (*from Graduate*)
Geoffrey Francis Chalmers
Harold Cecil Collins
Edsel Samuel Farris
Arthur William Gray
William Whilton Harvey (*from Associate*)
Leslie Bailey Hewett (*from Associate*)
Harold Derek Hoekstra
Norman John Howard (*from Associate*)
Harold Barry Lee (*from Graduate*)
Antoni Lewandowski (*from Graduate*)
James Gordon Mason (*from Graduate*)
John Norman Quick (*from Graduate*)
John Henry Risdon (*from Graduate*)
John Kevitt Rotherham
David Michael Scott (*from Graduate*)
Roman Władysław Szymanski (*from Graduate*)
Edward Stoops Thompson
Charles Frederick Toms (*from Associate*)
Alfred Eric Turner
Edward Maurice Ware (*ex-Graduate*)
Raymond Ernest Wilby (*from Associate*)
Wilfred Joseph Woods (*from Graduate*)

Associates

Robert Michael Crosley
Christopher Albert Clarke
Norman Leonard Pepperel Drake
Roy William Ellard
Stefanus Frederick William Furster
Norman Thomas Gwynn
Philip Edward Halsey
Eric Lupton
Desmond Francis Tooley
Leslie Mexborough Tucker (*ex-Student*)
Grahame Alfred Charles Waite

Graduates

Geoffrey Charles George Agg
Alan Edward Brock (*from Student*)
Peter Bonham Clay
Ronald Cole (*from Student*)
Gerald William East (*from Student*)
Peter Purdon Elliott
George Herbert Alexander Fenton (*from Student*)
Kenneth Allen Fisk
Anthony Desmond Fitness
Kenneth Thomas Fulton (*from Student*)
James Walter Gearing (*from Student*)
Raymond Alan Harrison (*from Student*)
Terence Henry John Heffernan
Geoffrey William Howard
John Alfred Howard
Albert Edward Hurren
Raymond Reginald Jessop
Albert William Kitchenside (*from Student*)
Kenneth Arthur John Lockwood
Alan Stewart Ryde
Gerald Frederick Short
Ronald Arthur Staines
Desmond Albert Thurgood (*from Student*)
Frederick James Travenen
John Brian Turtle (*from Student*)
Arthur Joseph Walls

Students

Roy Atkin
Peter Anthony Champion
John David Gabbott
Dennis Arthur Goswell
Roderick Cox Hastings
Brian Dutton Henshall
John Evans Hughes
Robert William Kelsall
Donald Edward Lennard
Andrew Denholm Mills
James Melville Norris
John Pryor
Dhanvada Madhava Rao
Edward Roger Roadnight
Reginald Alan Saunders
Wieslaw Andrzej Zaremba

Companion

Hugh Owen Bruce Grant

CHANGES OF ADDRESS

To assist in keeping the records of members correct and up to date the Secretary will be glad if all members will notify him as soon as possible of changes of address.

When notifying changes please give the following particulars:—

Name (in block letters).
Grade of membership.
New address (in block letters).
Old address.

Changes of address must be received *before the 15th of the month* in order to be effective for the JOURNAL for the following month.

JOURNAL BINDING

Members are reminded that a special leaflet on JOURNAL binding for the 1951 Volume and for 1952 was enclosed with the December JOURNAL. Copies of this leaflet are available on application to the Society.

ANNUAL SUBSCRIPTIONS

Members are reminded that their annual subscriptions became due on 1st January 1952. The rates are:—

	HOME	ABROAD
	£ s. d.	£ s. d.
Fellows	5 5 0	4 4 0
Associate Fellows	4 4 0	3 3 0
*Associates	3 3 0	3 3 0
Graduates (aged under 26) ...	2 2 0	2 2 0
Graduates (aged 26 and over) ...	2 12 6	2 12 6
Students (aged under 21)	1 1 0	1 1 0
Students (aged 21 and over) ...	1 11 6	1 11 6
Companions	3 3 0	3 3 0
Founder Members	2 2 0	2 2 0

* Any Associate elected before 1st October 1947 may, if he wishes, elect not to receive the JOURNAL, and in this case his subscription will be reduced by £1 1s. 0d. to £2 2s. 0d.

It will avoid delay and confusion if members, when sending remittances for subscriptions, will state their names clearly and give their addresses and grades of membership.

Remittances should be made payable to the Royal Aeronautical Society.

Modern Trends in Civil Airworthiness Requirements

by

WALTER TYE, O.B.E., F.R.Ae.S.

The 828th Lecture to be given before the Royal Aeronautical Society was delivered at the Institution of Civil Engineers, Great George Street, London, S.W.1, on the 18th October 1951. Mr. G. H. Dowty, F.R.Ae.S., Vice-President of the Society, presided and expressed the general regret at the continued absence of the President, Major Halford. He was glad to report that the President was progressing well and hoped to resume his Presidential duties before long.

Mr. Dowty then introduced the Lecturer, Mr. W. Tye, O.B.E., F.R.Ae.S., Chief Technical Officer of the Air Registration Board.

INTRODUCTION

Some liberties have been taken with the contents of the lecture in relation to the title. Firstly, it is proposed to examine safety in general, for only by this means can airworthiness be seen in its true perspective. Secondly, some trends in airworthiness and inter-related operational matters will be discussed. Finally, crashworthiness is dealt with at some length.

Although for convenience the lecture is presented in three Parts, there is a sequence of argument which links them. It is hoped to show that material improvements of safety are necessary before the aeroplane can be viewed as a wholly satisfactory means of transport. It seems improbable that these gains will be found in the airworthiness field. The task will be to maintain the satisfactory level of airworthiness achieved by aeroplanes of the past generation, and so to arrange matters that this can be done without great economic sacrifice. Improved safety may be found outside the area of airworthiness, for example in operational aspects, but the most profitable course—so far as the aeroplane itself is concerned—is to make it safer in a crash.

Much of the lecture is unashamedly speculative. For such speculations and expressions of opinion the author takes responsibility, but has indeed been grateful to his colleagues in the Board for their advice over a period of years without which he could not have given this lecture.

PART I

AIRWORTHINESS IN RELATION TO SAFETY

1. YARDSTICKS FOR MEASURING SAFETY

In all considerations of safety it is helpful to examine the past record. This immediately leads to a problem of choosing the scales on which safety can be measured. It is usual to quote a "damage" figure (*e.g.* numbers of accidents or fatalities) in relation to a "transport-use" figure (*e.g.* passenger-miles or aircraft-miles). Such yardsticks need to be treated with caution, as they may or may not give a realistic picture of what is happening, and often they are based on numbers so small as to have no statistical significance.

A figure used frequently is the number of passenger fatalities per 10^8 passenger-miles (*see* Fig. 1). For publicity purposes this figure has its merits, but in any particular year the figure usually depends on a small number of fatal accidents. Moreover, of all those involved in fatal accidents the number

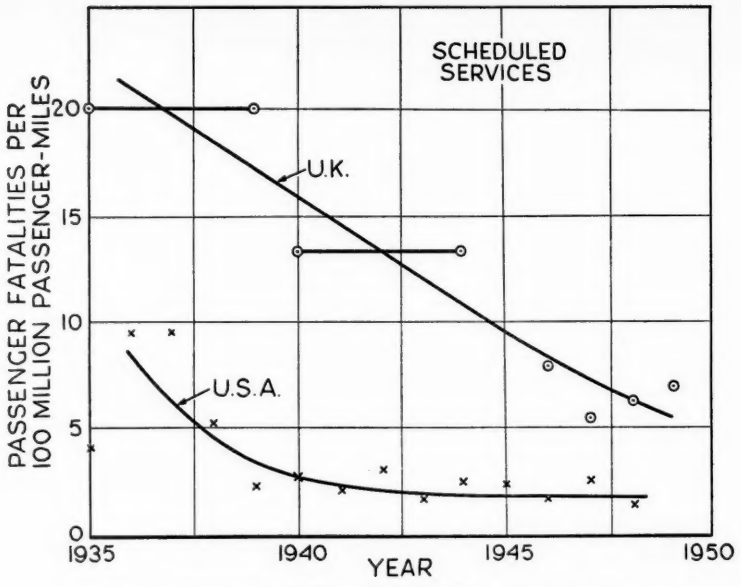

Fig. 1. Passenger fatalities per 100 million passenger-miles.

of passengers killed depends on many factors and is thus a very variable quantity.

Possibly a better picture is to distinguish between the fact of an accident occurring, and the result in terms of fatalities. On this basis a convenient measure of use is the distance travelled by the aeroplane, leading to an accident rate in terms of accidents per 10^6 aircraft-miles. Fig. 2 shows U.S.A.[1] and U.K.[2] figures plotted on this scale. The decrease of this figure over the past 15 years shows clearly that the liability for an accident to occur is steadily lessening. The percentage of fatalities to persons involved in all accidents is a measure of the overall liability of crashes to become catastrophes. This figure, which averages 13 per cent. for U.S.A. scheduled services over the past 10 years, shows no distinct trends with passage of time.

Other scales, such as engine-hours, or numbers of take-offs, provide appropriate yardsticks for detailed technical investigations of accident trends.

2. THE PASSENGERS' REQUIREMENTS FOR SAFETY

While examination of past records indicates improvements in safety, it does not answer the difficult question of whether the passenger is satisfied with the safety offered. In most forms of transport, the safety requirement of the passenger finds its own level, this process being aided by a balancing of safety and economics. In other words, in a financially self-supporting transport organisation, increase of safety bears a direct result in higher fares, and eventually the operator offers the highest safety compatible with the fare the traveller is willing to pay. This is unlikely to happen in aviation for at least two reasons. Firstly, aviation is so heavily subsidised that the levels of prices of tickets are largely fictitious. It is difficult to see any way in which the 50 persons who subsidise flying by their income tax can dictate the safety to be offered to the one person who flies. Secondly, in Great Britain the flying public largely comprises infrequent travellers, such as holiday makers, and regular travellers whose business renders any other means of transport impracticable. Neither of these classes of traveller is likely to indicate dissatisfaction by the usual method of choosing an alternative.

Any attempt to establish the safety requirements of the passenger is a highly speculative business, and in what follows it is hoped to provide a basis for discussion, for it is

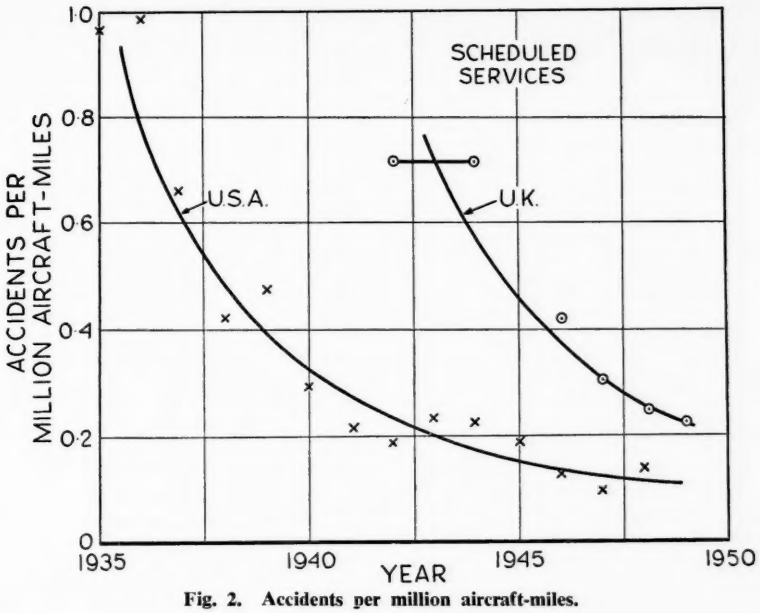

Fig. 2. Accidents per million aircraft-miles.

admitted that it is impossible to produce unequivocal arguments. Firstly, it is submitted that no normal person expects 100 per cent. safety. From everyday experience it is known that lives can end in a variety of unpleasant and unpremeditated ways, yet no abnormal precautions are taken to avoid such occurrences. Indeed to take all conceivable precautions would make life unbearable. While the risk obviously varies according to occupation, age, place of residence, and so on, it may be noted that one person in 1,000 dies accidentally each year in the U.S.A.*, and this gives a pointer to the order of risk which is accepted with equanimity.

The risk that will be accepted on a particular occasion probably depends largely on two factors, the advantage it is hoped to obtain by taking the risk, and the measure of control people believe they have over the circumstances. For example, although one person in 10,000 is killed each year on the road in Great Britain, individually people do not worry unduly because, rightly or wrongly, they feel they have a measure of control over the situation as it affects them personally. These two factors are seen clearly in private flying. On U.S.A. evidence the risk per hour of exposure is something between 1,000 and 5,000 times greater than that of normal life. But the private pilot derives sufficient pleasure, and believes in his ability to combat the risk, so he continues to fly.

In contrast with private flying, transport flying operates under a disadvantage in the respect that the passenger has to abandon all personal control of the situation. The sense of comfort which one derives from the knowledge that in the last resort one can get out and walk is absent. This is an important factor which leads to the passenger requiring a higher degree of safety than he otherwise would. A second important point is that the only means that the public has of assessing risk is on the basis of what it reads in the papers. Unfortunately, the number of persons killed in one aeroplane accident is sufficient to make it a headline item. The aeroplane therefore is at a disadvantage compared with the private car, which can quietly kill people at a not inconsiderable rate without the public gaining the same sense of catastrophe.

* Frequent reference is made to U.S.A. statistics as these were available in convenient form, and are probably reasonably applicable to British conditions.

For these reasons it is believed that for the flying public to feel content, the safety levels need to be at least comparable with those of surface transport, although possibly the advantage of speed offered by the aeroplane is sufficiently attractive to allow air travel to run at a higher risk rate than other means. Examine a few figures. Firstly, on a risk of hour-of-exposure basis, according to U.S.A. statistics the risk in good airline practice is from 50 to 100 times greater than it is if one is going about one's daily life on the ground. Secondly, compared with railways, the risk per mile travelled is about 10 times greater in the air than in the train. But the passenger is probably more interested in the risk for a particular journey, and since the typical air journey is say, 10 times as long as the typical train journey, the risk per journey is 100 times greater in the air than in the train. For reasons already mentioned the private car is not really comparable, but for what they are worth the figures show that the risk per mile in a private car is about the same as that of the airline. Again, on a journey basis, the distance travelled is small in a car so the journey-risk in the car is comparatively small. Figures for the risk at sea, which is phenomenally small, are not available, but on a distance basis, if the *Queen Elizabeth* ran at the same level as the airline, there would be from five to 10 deaths a year.

No particular significance is attributed to these comparative figures, except to indicate that aeroplane travel, even in well organised airline conditions, is still far short of the safety levels offered elsewhere. Whether the advantage of speed is sufficient to recompense the traveller for the present risks, is difficult to say. Personally, the author doubts it, and thinks the fact that there are many people who avoid flying if they can, or specially insure themselves whenever they fly, is an indication that there is some way to go before the passengers' requirement is fully satisfied.

These tentative conclusions have been reached ignoring the practical question of whether such increases of safety would result in the reduction of payload to zero. The equation for safety on the one hand, and cost of safety (in terms of, say reduction in payload) on the other, involves so many unassessable factors that it is doubtful whether any overall balance of one against the other can be shown. It is possible however to explore the technical possibilities of achieving gains in safety and at least an attempt can be made to assess which of the various methods is most likely to produce the largest gains at the smallest cost. The first step is to examine causes of accidents.

3. ACCIDENT CAUSES

The nature of modern air transport is such that there is an unlimited number of things which can, and do, go wrong, both in the aeroplane itself and in the activities of the persons concerned. In accident investigations it is not unusual to find, in addition to the direct causes of the accident, that a number of other potentially dangerous conditions existed. This is a reflection of the enormous difficulty of using a complex mechanism for routine transport purposes. It is this likelihood of faults occurring that leads to duplication and triplication. The designer is well aware of the engineering duplication, but it is to be found also in operational aspects. The consequence is that it is possible for a number of incidents to occur in a flight without an accident occurring. The accident is usually attributable to a combination or sequence of incidents, including both material and human elements. A by-product of this is to be found in the difficulty of pinning down the cause of a particular accident.

Bearing in mind this difficulty, the following figures can be viewed as a rough guide only. U.S.A. domestic airlines in the years 1940-1948[1] show the following average proportions:—

Material	24 %	
Personnel	50 %	(mostly pilot)
Remainder	26 %	

The annual figures (plotted in Fig. 3) show, for the material (*i.e.* lack of airworthiness) failures, a fall from 30 per cent. to 10 per cent. from 1940 to 1944, followed by a rise to 35 per cent. in 1948. This may be a consequence of the introduction of many types of aeroplane in the post-war years.

To obtain a more complete picture of accident causes, two sets of data have been examined more closely:—

(*a*) The official British Reports[3] on 35 accidents which occurred in the period 1946 to the present date, and six others of which particulars were available, on aeroplanes in the transport class (aeroplanes above 5,000 lb. weight with two or more engines, engaged in transport work carrying passengers or goods or making positioning flights). The

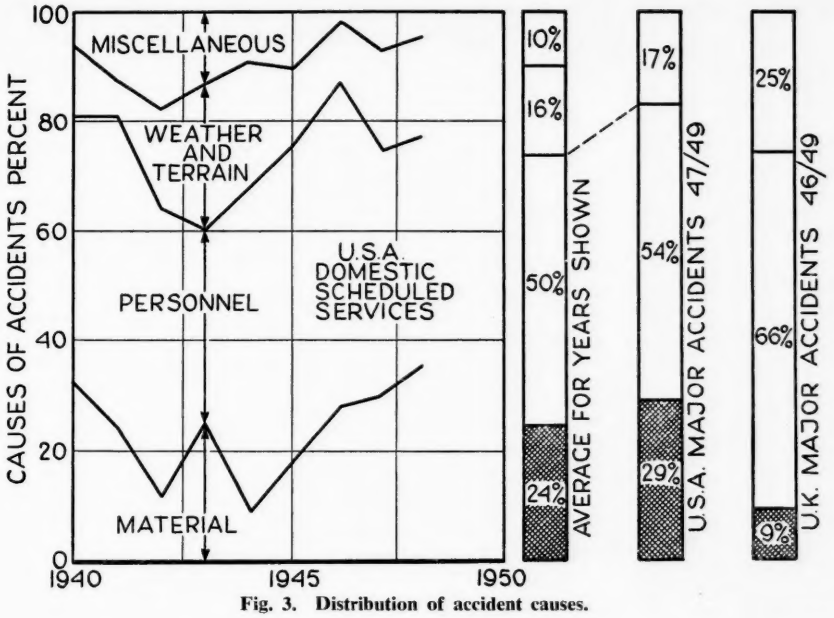

Fig. 3. Distribution of accident causes.

aeroplanes concerned were nearly all on the British Register, but included some of foreign construction.

(*b*) Summaries of American Reports[4] of about 60 major accidents in the period 1947-1949 on aeroplanes in the transport class engaged in transport work. These aeroplanes were all American-built and operated in the U.S.A.

The author has had to use his own judgment in allotting the causes of accidents, and where a particular accident showed a mixture of causes, a suitable allowance has been made. The results (*see* also Fig. 3) show:—

Cause of Accident Attributed to	*Percentage*		*U.K.*	*U.S.A.*
Lack of airworthiness			9	29
Pilot	62	66		
Other crew member	4		66	54
Operators' organisation	5			
Ground personnel (*e.g.* radio service)	10	25		
Undetermined and miscellaneous	10		25	17

These figures show that for U.S.A. operation the proportion for major accidents agrees with the previously quoted overall figures. They also show that in U.S.A. operation, in contrast with U.K. operation, the lack of airworthiness is an important factor.

On the latter point it seems likely that there are two underlying reasons. Firstly, the introduction of new types in the U.S.A. has probably resulted in relatively more accidents attributed to the aeroplane itself. This is borne out by the individual reports which quote fire in the air, inadvertent reversing of propellers, loss of propeller, structural failure in flight, and other such troubles which at present, fortunately, are rare in British operation. Secondly, it seems likely that operational causes (both pilot and ground service) are rarer in the U.S.A., and hence the airworthiness cause assumes more prominence. Possibly the generally better weather conditions in the U.S.A. assist in minimising operation causes, but it seems unlikely that this can be the sole reason.

In about 8 per cent. of the U.S.A. accidents, inadequate performance was a direct or contributory cause, the corresponding British figure being considerably smaller.

It seems therefore that for the general run of British operation the weak point is not lack of airworthiness, and that it will be found more profitable to attack the operational causes. Nevertheless, bearing in mind the apparent rise in the U.S.A. in airworthiness-caused accidents in the past few years, it is vitally important to maintain the good record.

4. PILOT ERROR ACCIDENTS

Consideration should also be given to whether pilot error can fairly be attributed wholly to human failure. May it not be that the task of flying, especially in emergency conditions, is so formidable as to make errors virtually unavoidable? If this is so, it may be that the task of the pilot should be lightened by the provision of better equipment.

A study of the previously quoted British accident reports shows that pure flying ability is rarely at fault. It seems possible that such factors as rapid response of the engine to opening the throttles in a baulked landing, and improved stalling qualities, might have helped in a few cases. The U.S.A. accidents shed more light on the latter point. Nearly one-quarter of the fatal accidents resulted from stalling, and half these occurred on one particular type. This type, which is an old one, is believed to have had stall characteristics substantially worse than the level set by modern requirements, so it is likely that, provided designers can make aeroplanes to meet modern requirements, stalling accidents will be kept at an irreducible minimum.

It has frequently been suggested that the sheer complexity of the pilot and crew controls and instruments is in itself a hazard. Little direct support can be found for this in analysis of accident causes. Nevertheless, it is felt that the simpler such controls are, the better able the pilot is to concentrate on avoiding getting into circumstances where he is in danger. One difficulty here is that there is little tangible information. The Americans are making very full studies of what they call human engineering, which is the practical application of the services psychology, physiology, and anthropology to the relationship of man and machines. There is little doubt that the engineer, who knows virtually nothing about the human element, has much to gain from such studies. A whole host of fields of investigation are obvious. To quote a few, the effects of vibration, ventilation, humidity, or fatigue, the pilot's response to visual and audible warnings, the accuracy and reliability of reading information presented in different manners, are of evident value. Methods of selection, training and maintaining a high standard of pilots and crews are also problems where a scientific knowledge of the human being will assist.

Where the pilot is often judged — it is suggested unfairly — to be at fault, is in navigation and making instrument approaches. It is significant that of the 41 British accidents examined, on 15 occasions the aeroplane was flying in bad visibility and struck the ground, in some cases during approach, in others while cruising. The author has little technical knowledge of the problems involved, but this is evidently a field in which improvement would reap considerable rewards. In many of these accidents for one reason or another the pilot was relying on his altimeter. Surely it is fundamentally wrong for the pilot to find himself in such circumstances, for the possible inaccuracy of the height reading is of the same order as the height margins during an approach.

The solution appears to be the development of approach and navigational aids which present information to the pilot accurately, reliably, and in a very simple form. Systems which require an acquired skill to interpret seem to be potentially dangerous. It is equally necessary that the pilot should have complete confidence in the accuracy of the information presented so that he is not tempted to embark on other potentially more hazardous procedures.

In Part III figures are quoted which indicate that 13 per cent. of fatalities are due to air collision. These accidents could surely be minimised by improved equipment. Also, about 10 per cent. of fatalities arise from ditching. Ditching is frequently due to getting lost, so again navigation is at the root of the trouble. It is evident that development of really successful navigation aids, approach aids, and collision warning indicators, would save far more lives than any improvement in pure airworthiness.

PART II

TRENDS IN AIRWORTHINESS

1. TRENDS IN DESIGN

In any assessment of future trends of airworthiness in particular, the magnitude of the task of making aeroplanes safe should never be under-estimated. It is nothing short of a technical miracle that such a complex mechanism as an aeroplane, operating in so unfavourable a medium as air, can be made

not only to fly but to bear some resemblance to a routine form of transport. The large direct, or indirect, subsidies on which civil aviation relies emphasise the cost of this near-miracle. The fundamental difficulties are all too familiar. The weight of every part of the aeroplane must be cut to a level unknown in normal engineering practice, and yet these parts must provide a degree of reliability compatible with reasonable safety. The sheer fact of relying on the movement of the vehicle to support itself, infinitely increases the need for reliability.

Superimposed on these difficulties are those which spring from the desire for increasing speed, range, payload, and scope of operational use. The demand for high speed has resulted in drawing more power from the engine and in increased wing loading. The former involves using materials to the limit, complexity of design, and cooling problems. Perhaps it is significant that modern performance requirements are based on the concept that at least one engine is inoperative. Increased wing loading, despite improved flap design, has increased stalling speeds by 50 per cent. to 100 per cent. of their pre-war values. These higher speeds greatly increase the pilot's difficulty, particularly in bad weather, since human reaction time has remained constant, but the distance travelled while the pilot reacts is much increased. Most important is the high impact speed when a crash occurs. In the early days a series of forced landings was commonplace and safe. Now any unintentional contact with the ground is a potential disaster.

In striving after maximum efficiency, the designer has had to provide systems of flaps, gills, retractable devices, feathering and reversing propellers, and so on, each depending on complicated hydraulics, electric and pneumatic systems. High altitude flying will soon take place in regions where knowledge of gusts and icing conditions is extremely limited, yet the aeroplane must be protected against these conditions. Again, high altitude has necessitated further systems to provide air at controlled pressures, temperatures and humidity.

The points to be emphasised are that modern demands are leading to more and more complexity, and the aeroplane is required to fly at higher speeds for longer distances, and under more onerous operating conditions, without detriment to payload. From the point of view of safety it would have been preferable if these advances had come more slowly so that extrapolation of past experience could have been more reliably based. This is, perhaps, wishful thinking, but it should be clear that if previous safety levels are to be maintained, and it is hoped, improved, the problems are by no means light.

2. TRENDS IN AIRWORTHINESS REGULATIONS

A cursory examination of the early civil airworthiness requirements of 1925 and those of to-day shows that the simple brief requirements of the past have been replaced by a vast and complicated system. But the aeroplane of 1925 was a very different engineering proposition from that of 1951, and the two changes are connected.

The early civil aeroplane owed its safety to its slowness, its short landing run, its use of simple engines, its freedom from accessories, its handsome strength margins, and its confined duties. Had aeroplanes stayed like this, airworthiness requirements would have done likewise. The modern aeroplane is potentially much more lethal than its predecessor and something has had to be done to keep such tendencies under control. The airworthiness authority has always been faced with a broad choice; to prohibit development, or to permit it, meeting potential dangers as they arise. Apart from one brief attempt by the U.S.A. to restrict stalling speeds, the author knows of no case where airworthiness authorities have followed the former course.

While the demands to make the aeroplane more efficient in terms of speed, range, payload, and ability to operate in diverse circumstances have grown, so also has the demand for safety increased. The form of modern requirements therefore is largely governed by steering a careful course between the demands of safety on the one hand, and economic efficiency on the other. This in turn means that the requirements must recognise fully the diversity of operational uses, the wide differences in design between one aeroplane and another, and the existence of the numerous gadgets. It would be a simple enough matter to pick out the most onerous conditions and to apply them regardless of whether they occurred in the particular circumstances. A moment's thought shows that this would ensure safety but with zero payload. Indeed, the greater the diversity

of the circumstances and the stronger the pressure for reasonable economic results, the more closely the requirements must match the exact circumstances—design or operational—which prevail in each particular case. There must be no hidden margins penalising 999 flights for the sake of the thousandth.

3. STRUCTURES REQUIREMENTS

The need to take circumstances into account has affected requirements in two main ways, the first lying within the field of pure airworthiness; the second involves inter-related airworthiness and operational considerations. Typical of the first are advances in structural requirements since 1935. In all these, the attempt has been made to relate the requirement to what are believed to be the fundamental factors affecting safety. The usual process has been to blend knowledge of strength levels which have been shown to be satisfactory in past experience, with theoretical and experimental evidence to indicate the general form which the requirements should take. It is perhaps a platitude to say that future action should always be based on intelligent extrapolation of past experience, but in fact this is the basis for most good requirements. Past development of structural requirements, although leading occasionally to greater strength margins, has mostly resulted in paring down strength margins, without detriment to safety and with considerable advantage to payload.

Examples of the requirements which have materially altered are:—

(*a*) Landing gear strength requirements have moved away from arbitrary loading conditions and now recognise the relationship of landing loads to the velocity of descent at impact, and the relationship of taxying loads to actual ground manœuvres.

(*b*) Flying boat hull loads have recently been improved in form by recognising characteristics, velocity of descent, impact angle, hull shape, and so on.

(*c*) Gust conditions are generally superseding the more arbitrary manœuvring load conditions for wing design, and the definition of the gust itself is becoming more in accordance with nature.

In most cases the rationalising process has now reached its limit and cannot advance until further basic data are available. Greater knowledge would probably allow further reductions of hidden and unnecessary strength margins, with advantage to payload. It is unfortunate therefore that the collection of loading statistics is proceeding very slowly.

The importance of requiring sufficient, but not too much, strength can be seen from the following example. To the author's knowledge, there has been only one fatal accident in British civil aviation attributable to gusts, in the past five years. This means not more than $2\frac{1}{2}$ per cent. of the fatal accidents are associated with this cause. To eliminate such accidents might mean an all round increase of strength of say, 10 per cent., and this in turn would reduce payload in typical cases by 5 per cent. to 10 per cent. In other words, a one per cent. loss of revenue would result in a saving of life of as little as $\frac{1}{4}$ per cent. to $\frac{1}{2}$ per cent.

4. PERFORMANCE REQUIREMENTS

By far the most advanced example of relating the airworthiness of the aeroplane to the operational circumstances is the modern system of performance requirements. Before the 1939-45 War, British practice was to impose stringent overall requirements in the form that take-off and landing distances must not exceed such and such values. These requirements led to a single value for the maximum allowable weight. It was then left to the pilot to reduce the weight if he felt it necessary, having regard to the circumstances of a particular flight. This assessment was mostly intuitive as there was little or no data available to assist his choice.

About 10 years ago the U.S.A. adopted a scheme of matching the aeroplane to the route and this has been further developed by the United Kingdom in recent years. Broadly, the British scheme is:—

(*a*) to determine the average performance (*i.e.* rates of climb, take-off and landing distances) for the type of aeroplane;

(*b*) to reduce these performance values by a margin to allow for aeroplane variability, giving a kind of "guaranteed" performance;

(*c*) to schedule these figures for a number of parameters which the operator either knows, or can forecast, for a particular flight, *e.g.* temperature, altitude, runway gradient, wind speed;

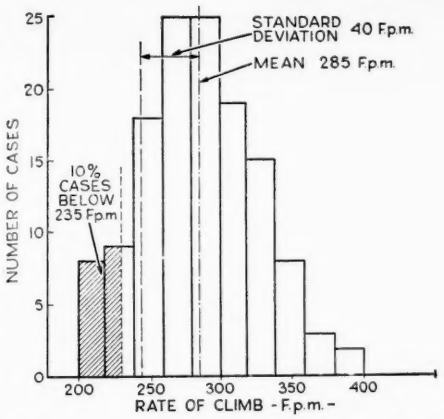

Fig. 4. Illustration of variation of rate of climb.

(*d*) to adjust the weight of the aeroplane for each flight so that, having regard to the known performance of the aeroplane and the operational circumstances of the particular flight, certain minimum margins are adhered to.

Thus, for example, the runway length, its altitude and gradient, the temperature, and the wind speed being known, the weight at which the aeroplane will just take-off with given safety margins is assessable. Similarly, the weight to clear obstacles surrounding the aerodrome, to clear high ground *en route*, and to land at the destination, are all calculable, and the lowest of these several weights dictates the maximum safe value for the trip. The object of this system is simply to permit the highest possible payload to be carried on every flight compatible with the demand that only on extremely rare occasions should the performance — in relation to the route—be less than a certain level. The pilot is free to reduce the weight below the calculated value, if from his knowledge of factors beyond the scope of calculation, he believes it safer to do so.

It is clear that once the decision is taken to treat performance as a factor which dictates weight, the possible economic consequences are so profound that there is no stopping half-way. It becomes necessary to give full credit for any alleviating circumstances. British work on this subject has been directed towards an even closer matching of performance with the route than was obtained under the original U.S.A. system.

Within the details of the airworthiness code every effort is made to take account of the aeroplane variables which bear on performance. This can best be understood by considering first the fact that no two apparently identical aeroplanes flying in apparently identical conditions develop exactly the same performance. Variations exist in drag, power, and pilot technique. These in turn depend on small differences in condition of the engine or airframe, and in inaccuracies of instruments, or in settings of flaps and so on. In the aggregate the differences are surprisingly large. For example, in a series of tests made by British European Airways[5] in which over 100 climb measurements were made on some 30 aeroplanes, the average (of the fleet) of the rate-of-climb with one engine cut and the other at take-off power, was 285 ft./min. On about 10 per cent. of occasions (*see* Fig. 4) the rate-of-climb was 50 ft./min. or more, lower than the average of the tests. So on say, one flight in 1,000 it is likely that variable factors would appear in a worse combination, reducing the available performance still further. The method[6] of developing the new performance requirements has been to assess the magnitude of the variance of the several factors, and then to sum the results to determine the drop in performance in terms of frequence of occurrence, checking the result by comparison with tests such as those just described.

Given this information, a certain "datum performance" may be selected for each stage of the flight, this being the minimum performance considered to be just acceptable to the pilot. The aeroplane is considered satisfactory if the performance falls to the datum on only one occasion in X, where X is a large number, in present requirements 100,000. To achieve this, the average performance of the fleet must exceed the datum by a margin corresponding to a frequency of ocurrence of one in X.

The effect of engine failure fits neatly into this scheme. If the average rate at which engine failure occurs is one in Y, and if X is small compared with Y, the performance margin primarily provides for variance of the aeroplane and barely at all for engine failure. If X is greater than Y, the performance margin makes due allowance for variance of the aeroplane and for the performance lost when one engine fails. Fig. 5 illustrates this point. The performance

margin is expressed as the gradient of climb, with all engines operating, for a particular flight stage, and is plotted against frequency of occurrence. If the aeroplane falling to the datum or below on one flight in two were satisfactory, then the performance margin would be zero (point *A*). (This involves an assumption that variance of performance is not "skew.")

Moving from point *A* to the right shows the gradual increase of margin with decreasing frequency of occurrence. This gradual increase, which is due to aeroplane variance, continues almost to point *B* which corresponds to the average rate of failure of one engine. At point *B* the sharp rise of performance, in effect, is the increase necessary to cope with the one-engine-failed condition. The curve then tends to flatten out until the frequency of occurrence of two independent failures of engines is reached at point *C*. The steps continue until, at the point where four independent failures is reached, the curve soars to infinity.

It is evident that much would be gained if the rate of engine failure could be so reduced that, where now failure of one engine is considered they could all be considered to be operating. The level of most current requirements corresponds to margins associated with rates of occurrence of 10^{-5}, which is in the middle of the one-engine-inoperative part of the curve. To achieve this same safety level, without taking account of engine failure, would necessitate moving point *B* well over to the right into the region of 10^{-6}. This would mean improving the present rates of engine failure 100-fold. Thus, although the gain in economy is attractive, the possibilities of achieving it are remote.

A more practical possibility is to reduce the variation of performance between one aeroplane and another. This variability is largely due to variation in engine power. Once the reasons for this are fully understood, it seems not unlikely that the variation could be reduced, for example by alteration of overhaul systems or periods. The gain in payload would almost certainly overwhelm any increased expenditure of ground servicing.

With this better understanding of the ingredients of performance it should be possible to find the best way of achieving a given level of safety with the least detriment to economy. For example, it is clear that the

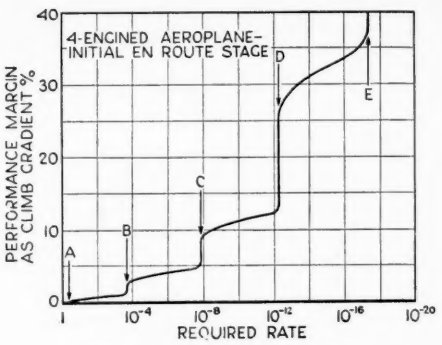

Fig. 5. Performance margin.

risk of performance falling below the datum is materially altered by small changes of required performance while one is between the steps. It pays therefore to work so far as possible at the foot of a step. On the other hand, no gain is achieved by working half-way up a step. Equally, if a gain in safety is sought which carries us from the foot of the step to its top, the penalty is high for a small reward. For example, if the power required, and hence power plant weight, were dictated by one-engine-inoperative conditions, and if for a four-engined aeroplane power plant weight was 20 per cent. of the gross weight, then if the same performance with two engines inoperative were to be required, the power plant weight would become 30 per cent. This increase might well absorb from half to all of the payload.

Accidents caused by lack of performance do not exceed, and in British operation are considerably less than, 8 per cent. of the total. To eliminate such accidents would probably mean, for some stage of the flight at present based on one-engine-inoperative conditions, jumping to two-engines-inoperative conditions. It comes to this therefore: with the improved understanding of performance, current requirements should achieve a reasonable reduction of performance-caused accidents, with no great economic penalty, but to go farther takes us into regions where the economic consequences become catastrophic.

5. EXTENDED FLIGHT TRIALS

The previous examples have dealt with efforts to match more exactly the

requirements to the surrounding circumstances. There is no time to give details of the other main aspect—requirements associated with the growing complexity of design. Since the safety of the aeroplane has come to depend on so many mechanisms and pieces of equipment, it is natural to find considerable emphasis in the requirements on these matters. When the comparatively rare airworthiness-caused accident does occur, it seems usually to be associated with some detail which has gone wrong in an unforeseen way. Once the cause of such accidents is known, they can generally be prevented with little or no economic penalty. The elimination of this kind of trouble depends largely on the ability to foresee contingencies, attention to detail, willingness to learn from past lessons, and rigorous testing.

One development only will be mentioned. Doubt has arisen whether normal ground and flight test methods will pick out all the dangerous points, particularly in such items as power plant installations, electrical and pressurisation equipment, or any relatively untried equipment. Early post - war experience showed that crops of defects occurred as soon as the aeroplane left the tender care of the constructor for the day-to-day rigour of operation. Therefore considerably more flying is now required before airworthiness certification. Ideally this extended flying covers a variety of matters. It subjects the aeroplane to the practical test of use in typical operating conditions as regards routes, crews, and maintenance. It is also possible to intensify the use of doubtful parts so as to simulate many months of operation in a few weeks. Experience is beginning to show that a considerable number of defects occur and are corrected in this practical testing period.

6. BROAD OR DETAILED REQUIREMENTS

In the previous paragraphs the technical reasons have been shown which have led away from the simple, rather arbitrary and usually penalising, requirements towards a more rational code which seeks to avoid penalties but is still quite specific in character. This problem might have been faced by other means, namely by writing rules in broad and more qualitative terms. Such a code could be as short and superficially simple as one cared to make it, but it would probably result in wide differences —in both the safety level achieved and the economic consequences. The choice depends on what is expected from the regulations. Thus:—

(*a*) in so far as regulations help to achieve a minimum airworthiness level, is it desired to set up a closely defined system so as to establish fair uniformity of the required level? or

(*b*) is it desired to ensure that in meeting airworthiness regulations there is uniform economic penalty?

Both these are associated with the fundamental reasons for having regulations at all. At the root of any system of regulations is a desire on the part of the majority to ensure reasonable equity. To hazard an analogy, few would enjoy a game in which there were no rules to determine the player's general conduct. A set of reasonable rules is preferred, with an understanding that no one can win if they are grossly infringed and with an impartial referee to interpret the doubtful points. Surely some similar feeling underlies the airworthiness rules.

Everyone wants a satisfactory record of safety to be established. No one wishes this to be jeopardised by the odd man taking risks. It is recognised that provision of safety has its drawbacks in terms of payload, but these are more bearable if the burden is carried by all.

In Great Britain the Board has endeavoured to prepare requirements aimed at a uniform minimum level of airworthiness. It has not been concerned if aeroplane A achieves this object by more efficient means than aeroplane B, with the result that A offers a higher payload than B. The Board has been limited in many cases by sheer inadequacy of knowledge. For example, the requirements for manœuvring loads in flight which are sometimes responsible for determining maximum weight: for two different types of the same gross weight the same manœuvring load factors are required. It is quite likely that other circumstances of design, such as pilot's control effort, have a bearing on the manœuvring loads sustained by the aeroplane, but there are no facts on which to work. Given such facts, the Board would be willing to write the requirement in the form that on not more than one occasion in X must the aeroplane reach its proof load in flight manœuvres. This would be an "equal safety" requirement in its purist

form. Without the information all that can be done is to specify a given manœuvring load factor. This may well result in an aeroplane having 10 per cent. more or less strength than equal safety considerations would dictate. Now, even though there may be this lack of certainty about the requirement itself, the strength is expected to be proved within fairly close limits to meet the requirement. To this extent equitable treatment from the viewpoint of the economic consequences enters into the question. However, within limitations set by the lack of knowledge, it is the Board's intention to consider only uniformity of the safety level.

It is uncertain whether this view is held elsewhere. Although I.C.A.O. discussions are nominally on the basis of uniformity of safety levels it is felt that equity of economics lurks in the background. This has been most noticeable in performance matters where payload is likely to be seriously affected. Some States give clear evidence of a desire to set up requirements in considerable detail—far more detail than the ability to achieve uniform safety could possibly demand. It seems therefore that those who seek such detail must be concerned, not that X is possibly slightly less safe than Y, but that X is getting away with more payload than Y. This is an unfortunate trend, but because of the impossibility of ever agreeing internationally on the consequential mass of detail it is probably but transitory.

Whether uniform safety or equity in economic consequences is sought has a marked bearing on the form the requirements take. If the former is the target there will be more flexibility and less detail in the requirements. With the former as the broad aim in British legislation it is necessary to state as precisely as possible the basic intention, and to couple this with interpretative detail which establishes with more precision the level of airworthiness implied. The interpretative detail is treated flexibly and if good reasons are advanced to show that the main object has been achieved there is nothing to prevent departure from the detail. Once the concept is accepted that the requirements should govern precisely economic results, the interpretative material becomes much more rigid and comprehensive.

Looking back on the past few years, the Board's requirements began life in a fairly broad qualitative form. Experience showed that this would admit very wide differences of airworthiness, so interpretative detail has been added more precisely to state the level. The influence of I.C.A.O. has been to reduce the flexibility of interpretation. The author's forecast is that, as the fund of information grows, and with a change of heart in I.C.A.O., a slow move to requirements of a more basic form may be expected. By this it is not meant that loose qualitative requirements should be expected, but rather that as the fundamental basis for a requirement is better understood, the requirement can be written precisely but briefly.

Meanwhile it is believed that the detail of present requirements has done more good than harm. That requirements are but a small factor in ensuring safety is not disputed. Also, there is no doubt that much of any reasonable code of requirements would be voluntarily followed. There are, however, such an enormous number of features of aeroplane design which with relatively small differences can make, and have made, the difference between safety and danger, that a code of requirements is an ever necessary reminder. Moreover, it is often a feat of imagination to relate a potential danger point with the occurrence of an accident. It is these improbable things which cause accidents—as nearly every accident shows—and it is the job of requirements to bring to attention such possibilities so that they may be eliminated.

PART III

CRASHWORTHINESS

1. INTRODUCTION

A distinct trend in modern airworthiness is the growing emphasis on the need to protect the occupants of an aeroplane in a crash. The underlying thought is simple. Only a small proportion of accidents are now due to lack of airworthiness, therefore, even where it is technically and economically practicable to improve airworthiness, the accident rate cannot be improved greatly through such means. On the other hand, if protection in the crash is improved, lives may be saved in nearly all types of accident, regardless of the cause. Moreover, it is likely

that for a given expenditure of weight, improved crashworthiness provisions will save more lives than would improved airworthiness provisions.

2. TYPES OF ACCIDENT

Before examining crashworthiness in detail, it is useful to see how various types of accident are distributed. An analysis of 66 major accidents to American[4] and British[3] civil transport aeroplanes showed that they were distributed as follows. The corresponding proportions of fatalities have been roughly calculated (*see* Fig. 6):—

	Percentage accidents	*Percentage fatalities*
Land impact	80	77
Collision in the air	8	13
Sinking in water	12	10

It is doubtful whether crash provisions can ever safeguard the air collision. Fortunately they are a relatively small proportion. Clearly there is most to be gained by studying the land impact cases.

3. LAND IMPACT ACCIDENTS

In the following examination the terms will be used:—

Non-fatal accident —An accident in which all occupants survive

Fatal accident —An accident in which some or all are killed

Partly-fatal accident—An accident in which some, but not all, are killed

Fully-fatal accident —An accident in which all are killed.

An analysis of American and British major accidents on transport aeroplanes for the years 1946/1949 (*see* Table I) shows that for over 50 accidents in which the aeroplane struck the ground (in contrast with ditching or air collision)

36 per cent. were non-fatal
45 per cent. were partly-fatal
19 per cent. were fully-fatal.

Fig. 7 shows that the numbers of persons (totalling about 1,300) involved in these three classes of accident were distributed in about the same proportions as the accidents themselves. It is inferred that size of aeroplane has no marked bearing on the result.

In the partly-fatal accidents, the proportions of fatalities were fairly uniformly distributed between one per cent. and 99 per cent., as shown in Fig. 8. In these partly-fatal accidents, on the average a little over half the occupants were killed. It follows that for every 100 persons involved in fatal

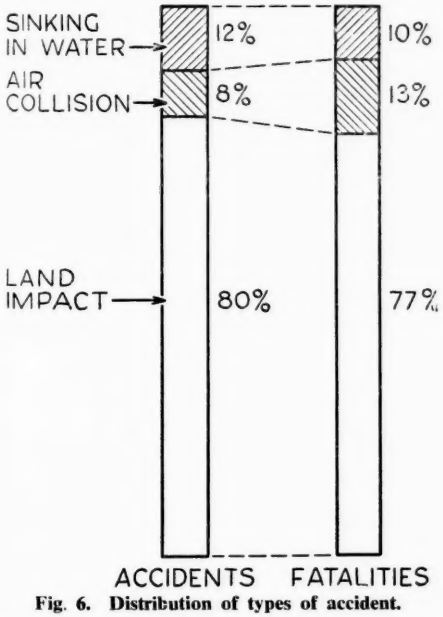

Fig. 6. Distribution of types of accident.

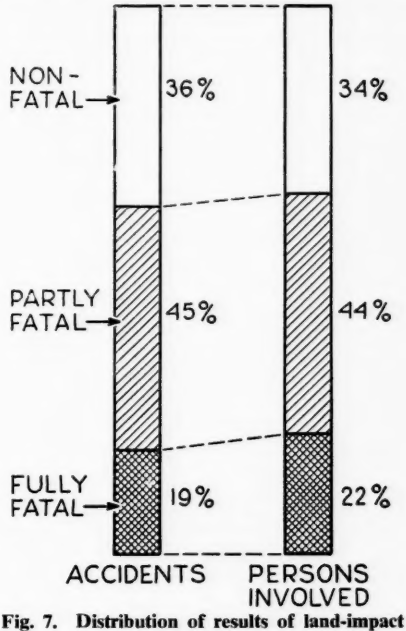

Fig. 7. Distribution of results of land-impact crashes.

accidents about 70 are killed, half of whom are in fully-fatal accidents, and half in partly-fatal accidents. It is significant that the percentage of fatalities in fatal accidents is so high. There is something about accidents which leads to the result that if fatalities occur at all, then they occur on a devastating scale.

It is submitted that in a partly-fatal accident, since one or more persons survive, the accident is *potentially survivable*. By suitable design provisions it should be possible to save many more, if not all, of the occupants. If all were saved in partly-fatal accidents, one person in two at present killed in land impacts would be saved.

4. EFFECTS OF SPEED AND OUTBREAK OF FIRE IN LAND IMPACTS

In the 50 or so accidents analysed it was known whether or not fire occurred, and also some idea could be formed of the speed of impact. In Table I the accidents are accordingly divided into four groups. The table also distinguishes between partly-fatal and fully-fatal accidents; by the method shown in the Appendix, the figures have been converted into an equivalent number of fully-fatal accidents, as this gives a more direct measure of the proportion of fatalities to

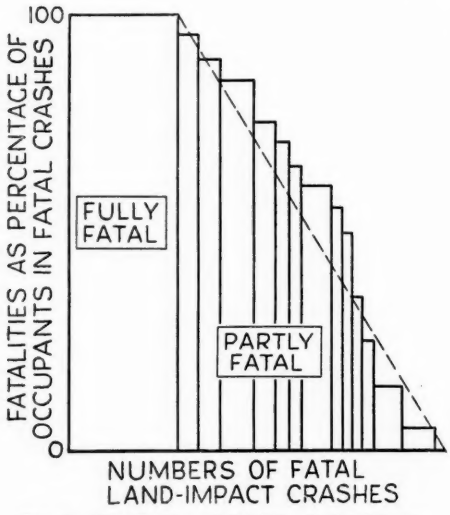

Fig. 8. Distribution of fatalities in fatal land-impact crashes.

TABLE I

ANALYSIS OF MAJOR LAND-IMPACT ACCIDENTS TO AMERICAN AND BRITISH CIVIL TRANSPORT AEROPLANES 1946/1949

	Low speed		*High speed*		*Total*
Accidents	*Without fire*	*With fire*	*Without fire*	*With fire*	
Fully fatal	2	4	1	3	10
Partly fatal	10	10	1	3	24
Non-fatal	12	6	1	0	19
Total	24	20	3	6	53
Equivalent number of fully fatal accidents	5.3	10.4	1.9	5.5	23.1
					Average
Fatality ratio %	22	52	64	92	44

numbers of persons involved. In the following pages this sample of accidents is analysed and various conclusions are drawn. It is realised that the conclusions are not likely to be numerically accurate, but so far as possible the estimates have been checked by reference to other estimates of a similar kind, and from this it is believed that the figures which follow form a fair and representative guide.

Considering first the effects of speed only, less than one-fifth of the accidents were of the high speed type. In the high speed accidents the fatality ratio (*i.e.* persons killed as a percentage of total persons involved) was high, about 80 per cent., while for the low speed accidents it was low, about 35 per cent. (*see* Table II and Fig. 9). Considering next the effects of fire, in about half the accidents fire occurred, and in these the fatality ratio was about 60 per cent., while in those in which fire did not occur the fatality ratio was about 25 per cent.

Figure 10 shows the accidents broken down into four groups, and it is evident that,

(*a*) if speed is high, regardless of whether or not fire occurs, the fatality ratio is high (65 to 90 per cent.), but the figure for "without fire" is based on three cases only, so it is not reliable;

(*b*) in the low speed accidents, the outbreak of fire increases the fatality ratio from about 20 to 50 per cent.

If crash risks are to be reduced there are broadly two courses to follow:—

(*a*) to see whether impact speeds can be reduced, and

(*b*) to minimise the consequences of impact —both the direct mutilation of the occupants and the outbreak of fire.

TABLE II

LAND-IMPACT FATALITY RATIOS

	Low speed	*High speed*	*Average*
Without fire	22	64	27
With fire	52	92	61
Average	36	82	44

5. REDUCTION OF IMPACT SPEED

Examination of accident records shows that the land impact cases fall into three groups:—

(*a*) those where impact occurs unexpectedly in cruising flight (*i.e.* the typical flying into a hillside accident);

(*b*) those where control is lost and the aeroplane dives to the ground; these are relatively few and can be ignored in the following examination (only two of the nine high-speed cases quoted were of this class);

(*c*) those where impact occurs unexpectedly during approach or following a missed approach, or soon after take-off, or in a forced landing, or following a stall near the ground.

Broadly speaking, the high speed cases occur at cruising speed or thereabouts, and the low speed cases at the stall or a little above the stall. The cruising speed of an aeroplane is accepted as fundamental to its usefulness as a vehicle, so it is a forlorn hope to suggest reducing this speed. The primary solution for dealing with these accidents rests not in crashworthiness, but in the elimination of the cause of the accident.

In the low speed cases, while improved approach aids would assist greatly, since the speed concerned is a function of stalling speed, reduction of the latter would obviously be beneficial. Sir Frederick Handley Page devoted the Third Louis Bleriot Lecture[7] to a discussion of the advantages of slower minimum flying speeds and to the technical methods of achieving them. There is nothing to add to his statements, other than to point to the accident figures which support his views.

A little more evidence on this subject can be gained by dividing the low speed accidents into two classes—low and high stalling speed. In the sample examined over half the aeroplanes had a stalling speed of about 70-80 m.p.h., and for these the low-speed impact fatality ratio was 25 per cent. The remaining aeroplanes had considerably

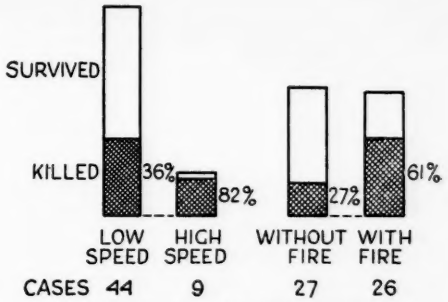

Fig. 9. Distribution of fatalities according to speed of impact and occurrence of fire.

higher stalling speeds, and the fatality ratio was 50 per cent. Some speculation may be made on possible trends. As time goes on the low stalling speed aeroplanes are being replaced by high stalling speed aeroplanes, and cruising speeds are also increasing. It is a reasonable guess that, if nothing is done to improve matters, the fatality ratio in future low-speed cases will increase from about 35 per cent. to around 50 per cent. while in the high speed accidents it may increase from about 80 per cent. to 90 per cent. In terms of total deaths in land impacts this means an increase of about 30 per cent. compared with the past record. Fig. 11 pictures this rather gloomy prospect.

On the other hand, if stalling speeds of all aeroplanes were reduced to about 75 m.p.h., the low-speed accident fatality ratio would probably reduce from 35 per cent. to 25 per cent. This reduction more than counterbalances the potential increase in fatality ratio in the high speed cases, giving an overall improvement of about 20 per cent. It may be felt that this improvement is relatively small when the difficulty of

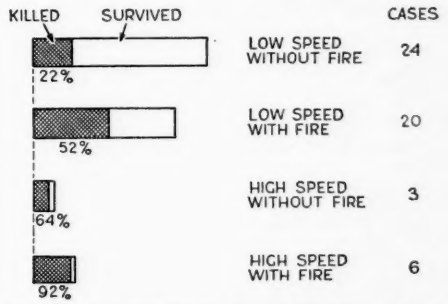

Fig. 10. Detailed distribution of fatalities in land-impact crashes.

reducing stalling speed is considered, but it must not be forgotten that if stalling speed were kept low, many of the accidents might not occur at all, and no credit has been taken for this. Moreover, if the high-speed cases were eliminated by improved navigational aids, the emphasis would then fall more fully on reduction of the fatality ratio of the low-speed cases. For the low-speed cases separately the difference in fatalities between a fleet of high stalling speed aeroplanes and low stalling speed aeroplanes is of the order of 2 : 1.

There are no transport aeroplanes with really low stalling speeds (*e.g.* 50-60 m.p.h.) on which to draw conclusions, but examination of the records of accidents to small aeroplanes shows that with stalling speeds in this region the low speed class of accident is rarely fatal. Therefore it comes to this: if the attack is confined to stalling speed only, worth while gains would accrue if the speed were kept down to 75 m.p.h., while reduction to 50 m.p.h. might reduce the low speed impact risk virtually to zero. However, in view of the difficulties of achieving this it is wise to study other possibilities of minimising risk by suitable internal design.

6. CRASH ACCELERATIONS AND AEROPLANE DAMAGE

For obvious reasons, an aeroplane usually hits the ground more or less nose first. In fairly level impacts, damage may be slight and confined to the under surfaces. In nose-down crashes the energy is absorbed more by crushing the nose structure than in sliding friction. The massive wing structure usually protects the aft portion of the fuselage. The retardation of the aeroplane, and hence the inertia forces on the occupants, lie more or less along the axis of the fuselage although there are often small vertical and lateral components of force.

There is a little evidence to show that in the gentler level types of crash, accelerations of 1 *g* to 10 *g* occur; while in the nose-down crash, accelerations probably vary from 5 *g* to 20 *g*, and in rare cases are probably higher. There is also a little evidence which suggests that whereas the front fuselage crushes in nose-first crashes when the accelerations exceed 5 *g* and 10 *g*, the rear fuselage remains intact with accelerations of 20 *g* or more. Little substantiation of these figures can be offered, but for working purposes they are a reasonable guide.

Although providing no direct evidence, it is of interest to note that if an aeroplane comes to rest under a uniform acceleration of 20 *g*, the distance involved is fairly small. Fig. 12 shows the stopping distances of several aeroplanes when flying initially at approach speed and then subject to a retardation of 20 *g*. On this diagram is shown the length of the fuselage of each aeroplane and a black dot marks a point 30 per cent. of the fuselage length from the nose. It will be seen that, to a close approximation, the stopping distance required is 30 per cent. of the fuselage length. Now, in a head-on crash in which energy is absorbed by crushing the nose it is often about the front 30 per cent. of the length which is destroyed. Hence, it can be inferred that provided the rear fuselage stands the retardation of 20 *g*, the crushing of the front fuselage provides a sufficient stopping distance for crashes up to approach speeds. Alternatively the results can be expressed by saying that if the aeroplane slides its own length in a crash at approach speed, the mean acceleration is as low as 6 *g*.

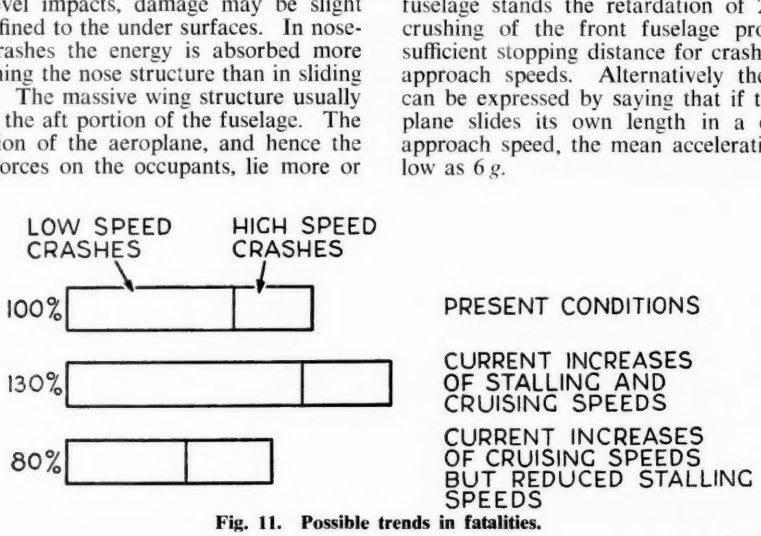

Fig. 11. Possible trends in fatalities.

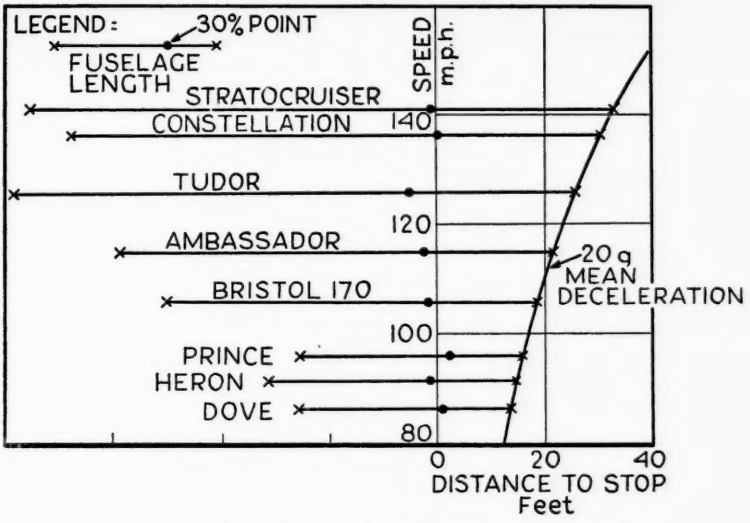

Fig. 12. Distance to stop in crashes at approach speed.

7. CAPACITY OF THE HUMAN BODY

The nature of the injuries depends largely on whether the aeroplane structure and the seats and safety belts remain intact. If the belt fails the body is projected violently against whatever lies ahead and all manner of injuries result. If the belts and seats hold, injuries in "straight" crashes are almost wholly confined to head injuries caused by the passenger's head striking the back of the seat ahead, or such objects as window frames. Damage to the abdomen caused by the body "jack-knifing" forward over the safety belt is rare. In over 100 case histories examined by Cornell University, where the person concerned survived despite breakage of the safety belt, less than two per cent. showed evidence of abdominal injuries. In many cases the belts in use had a nominal strength of 2,000 lb., and from extensive dynamic testing the average strength of the belts was known to be 2,800 lb. Thus, if the average weight of the persons concerned were 160 lb., the crash accelerations survived were of the order of 17 *g* to 18 *g*. Fracture of the spine is also rare. When internal injuries and spinal fractions occur they often appear to be due to lateral forces such as would be experienced in violent ground loops or cartwheels. Individual cases are on record where persons have withstood estimated crash accelerations of 40 *g* when wearing belts of the normal type.

When a shoulder harness is worn, the accelerations which the body can sustain are probably higher. There are cases where 40 *g* harnesses have broken without serious injury to the occupant. The earlier idea that the neck would be broken is without foundation. U.S. Air Force experiments with persons adequately supported have established that accelerations of 35 *g* can be sustained with no worse effect than that of indulging in brief violent exercise. Undoubtedly, in a backward-facing seat with support for the back of the head, which gives better support than does the harness, crash accelerations greater than 40 *g* could be survived.

The vulnerability of the head is indicated by evidence* that if the head strikes a hard and unyielding object at about 16 ft./sec., fracture of the skull may occur. If, however, the object struck yields, and is otherwise suitably designed, much higher impact speeds (50 to 100 ft./sec.) can be withstood. Research in the Cornell Laboratories, with a full-scale dummy man, indicate head impact

*The author is specially indebted to Mr. Hugh de Haven, Director of Crash Injury Research of Cornell University Medical College for much of the information on crash injury. This organisation has taken a leading part in this class of research.

speeds of 40 ft./sec. in 10 *g* crash cases, and of the order of 60 ft./sec. in 20 *g* crash cases. It is therefore well within the realms of possibility to minimise the effects of head impact by suitable design of the objects within striking range of the head.

To conclude,

(*a*) A belt of normal arrangement offers adequate protection for crash accelerations at least as high as 20 *g*, provided that the head does not strike objects as the body "jack-knifes," and provided that high lateral forces are absent.

(*b*) For higher accelerations, a shoulder harness or backward-facing seat is desirable, and given such equipment, accelerations of 30-40 *g* can be withstood (probably much higher with the backward-facing seat). Such equipment may also give better protection when lateral components of force are present.

8. STRUCTURAL LIMITATIONS TO IMPROVEMENT

Since it is clear that, if properly supported, the human frame can cope with crash forces better than the aeroplane itself, the structural problems must be reconsidered. There seems to be little prospect of improving, without serious weight penalty, the strength of the fuselage itself against crash loads. It is fundamental that energy has to be absorbed, and while fuselages project forward of the wing it is this part which must absorb it. If the forward fuselage were reinforced in strength, it would not necessarily be more effective as a shock absorber. Further study might usefully be given to the best design of fuselage to minimise the structural damage in absorbing crash energy. An obvious practical step is to remove as many occupants as possible from the front and to place them in relative safety aft of the wing. In some aeroplanes such compartments as galleys, lavatories, and wardrobes, could be placed forward instead of aft, with considerable advantages to crashworthiness.

However, there may remain a residual number of passengers and crew members in compartments forward of the wing. Little would be gained by providing seats and belts of a strength level substantially greater than that corresponding to major disintegration of the cabin. Thus it would be fruitless to use seats and belts above about 10 *g* strength in present types of forward fuselages and above about 20 *g* in rear fuselages. There are three courses open:—

(*a*) to provide 10 *g* seats throughout, sacrificing the lives of passengers in the aft cabin;

(*b*) to provide 20 *g* seats throughout, causing an unnecessary weight penalty in the forward cabin;

(*c*) to provide 10 *g* seats forward and 20 *g* seats aft.

British legislation has so far pursued course (*a*), but the author favours (*c*). The objection to (*c*) is that it discriminates between the occupants' safety and leads to a kind of First Class and Third Class compartment. But the plain facts are that with present design of aeroplanes there is a fundamental difference in the safety of the front and rear. Either a Nelsonian eye can be turned to this, or maximum advantage can be taken of whatever protection the basic design offers. The author prefers the latter view. It is only a matter of time before the better informed passenger will realise that there is a basic difference so that what is done with the seats is unlikely to alter the potential objection to the varying level of safety inherent in present types of aeroplanes.

9. PRACTICAL POSSIBILITIES OF IMPROVING CABIN DESIGN

The maximum advantage should be taken of the protection offered by the aeroplane structure by minimising the number of occupants forward of the wing, and by providing 10 *g* seats, belts, and attachments, in forward compartments, and 20 *g* strength in aft compartments. Estimates of the weight of seats, belts and floor structure compared with present design based on 6 *g* strength, suggests an increase of about 5 lb. for 10 *g* seats, and 15 lb. for 20 *g* seats. Taking the weight of a passenger and his luggage as 200 lb., this would mean in a typical case a loss of revenue of 6½ per cent.

To protect the passenger from damage to the head during the crash there are several possibilities including,

(*a*) reversing the seats so that they face aft;

(*b*) using widely spaced forward-facing seats;

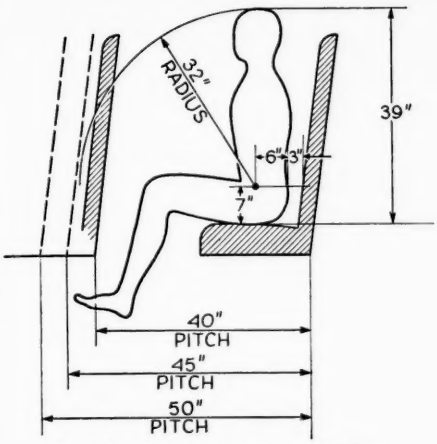

Fig. 13. Forward-facing seat spacing.

(*c*) using seats facing each other—Pullman car fashion.

There is no doubt that the backward-facing seat with the seat back sufficiently tall to support the head offers ideal protection. It should also assist when there is a lateral component of force. The objection is invariably raised that for one reason or another passengers would not like facing backwards. Such evidence as the author has seen points to precisely the opposite conclusion, but it is fruitless to enter into a dispute about persons' reactions without an adequate survey of these reactions. Meanwhile, it is contended that those who object to backward-facing seats have no solid justification for their beliefs. In view of the advantages to safety, and bearing in mind that for the past 10 years persons concerned with safety have been emphasising this advantage, it is a shocking state of affairs that no one has yet made full-scale trials in civil operation to establish the truth of the question of passenger reactions. It is only a matter of time before public opinion will demand what the author believes should already have been offered.

Widely spaced forward-facing seats are reasonably satisfactory for safety. It is important to protect the occupant from a glancing blow against the cabin wall and window frames, but this should not be an insuperable difficulty. By wide spacing is meant 45 in. to 50 in. pitch between seat rows, the latter being necessary if the seat back has pronounced rake. Fig. 13 illustrates how with conventional close spacing (40 in. pitch) the back of the seat ahead is ideally placed to do damage. In drawing this picture the seated height of a tall man was taken from medical statistics to be 39 in. and an allowance was made of 3 in. forward movement for looseness of the safety belt. Spacing of 45 in. or more is unattractive for high-capacity short-range aeroplanes, which throws into prominence the alternative of backward-facing seats.

Seats facing each other are of value if properly used. The half of the passengers facing backwards have the full advantage of backward-facing seats. The other forward-facing half are protected provided that the spacing is sufficient to prevent impact of the head on the opposite person's knees. A seat pitch of about 45 in. is sufficient for seats with moderate rake. Thus, there is no gain over widely spaced forward-facing seats throughout. If a table is fitted between rows of seats this could be safe provided that the forward-facing passengers were drilled to lay their heads, shielded by the arms, on the table. However, the author has no great confidence in pre-crash drills, and in many accidents there is little fore-knowledge that a crash is about to occur.

These three methods aim at preventing the passenger's head from striking other objects. This is undoubtedly the most certain method of protection. As mentioned earlier, there is some reason to believe that objects lying in striking range could be rendered fairly harmless by suitable design. Whether this approach could ever be as satisfactory as preventing collision of the head is not yet clear. But as a palliative, and particularly while the majority of aeroplanes employ closely spaced forward-facing seats, proper design of all contact points should be fully exploited. The objects should be to provide "plastic" yielding under impact and to spread the area of contact. Thus, rigid structures with sharp edges are most objectionable. When the seat back is a conventional tubular structure, large diameter thin gauge tube is preferable to small diameter thick gauge tube. Adequate padding should be employed. Rubber and other elastic materials are unsuitable as they cause a rebound. Preferably materials which absorb and retain the energy of impact should be used. Research in the Cornell Laboratory has shown that 2 in. thickness of material of the plastic foam type, covered with very thin

low strength aluminium alloy sheet is very satisfactory for flat panels.

The design of seats themselves requires further study. In a crash the overall acceleration is determined by the speed of impact and stopping distance, but the acceleration at any moment probably varies greatly from the mean. These very high short - duration accelerations could be smoothed out by providing plenty of plastic deflection of the seat and belt arrangement. It is believed that a seat which absorbs the maximum energy before it finally breaks is best suited to the purpose, provided that it does not close like a mouse trap on the occupant.

10. SAVING OF LIFE CONSEQUENT ON IMPROVED CABIN ARRANGEMENT AND SEAT DESIGN

Estimates of saving life are bound to be speculative as there is little evidence yet of the results of crashes of aeroplanes employing backward-facing seats. An R.A.F. Hastings, in which all 25 passengers survived, crashed spectacularly but it is unlikely that the crash forces were severe. The most interesting feature was that the high backs of the seats protected the passengers' heads from the luggage rails and the cabin roof which collapsed. A Valetta crashed in February 1951, and of the 19 passengers seated facing aft, 14 were uninjured, while 5 received various injuries caused by damage to the fuselage structure as a whole. The crash acceleration was estimated to be an average of 10 *g*. This second accident is a good example of the virtues of sound cabin arrangement.

The full advantage of good cabin arrangement can only be obtained if fire is avoided. In other words, some persons may be saved from mutilation only to burn to death. It is useful therefore to attempt three estimates of saving life:—

Leaving cabin arrangement unaltered but eliminating fire;

Improving cabin arrangement but leaving the fire risk unaltered;

Improving cabin arrangement and eliminating fire.

For the purpose of these estimates the sample of Table I has been used. Such estimates clearly involve a certain amount of guesswork so no great reliance can be placed on the results other than to provide a general pointer. In making these assessments the method was to study each group of accidents in Table I and to consider the prospect of improvements in each group. For example the prospects of improving low-speed cases are clearly better than the high-speed cases. Where doubt was felt, a pessimistic and an optimistic assessment was made with the following results (*see also* Fig. 14):—

(*a*) Leaving cabin arrangement unaltered but eliminating fire—33 per cent. lives saved.

(b) Improving cabin arrangement but leaving fire risk unaltered—savings between 12 per cent. and 39 per cent., average 25 per cent.

(*c*) Improving cabin arrangement and eliminating fire—savings between 43 per cent. and 71 per cent., average 57 per cent.

Total elimination of fire is probably a remote and impracticable ideal, but, if steps could be taken to halve the incidence of fire, the savings are well worth while. Even with existing fire risks there is a valuable saving purely from cabin arrangement. At this point it is worth noting the balance of safety and the cost of safety aspect. The average figure for 25 per cent. saving consequent on improved cabin arrangement, represents a saving in all types of crashes of about 20 per cent., and this would cost a loss of revenue of 6.5 per cent., or 3 per cent. saving of life for one per cent. loss of revenue. This is a ten times more favourable rate of exchange than that given by a previous example of improved airworthiness.

11. POSSIBILITIES OF PREVENTION OF CRASH FIRES

The principles for preventing crash fires are simply to prevent the readily ignitable materials from coming into contact with possible sources of ignition. In practice this has been singularly unsuccessful. Because of the difficulty in a crash of containing the ignitable materials (principally fuel and oil) in the places where they belong, it is necessary to resort to attempts to keep the source of ignition and combustible materials as far apart as possible, but again there is not much room for this. Another device is to attempt to suppress sources of ignition.

It has long been the hope of everyone that an aviation fuel might be developed which would not catch fire so readily or so viciously

as does petrol. The use of paraffin may show some advantages, but operational experience of paraffin-driven turbine-engined civil aeroplanes is necessary to prove the case. Analysis of accidents of military aeroplanes does not, unfortunately, offer good reason to hope that the risk of outbreak of crash fires will be reduced in the paraffin-driven turbine-engined aeroplane in comparison with the petrol - driven reciprocating - engined aeroplane.

A major fire can only be caused by the release of large quantities of inflammable fluid, so clearly fuel is the first risk, with oil and hydraulic fluid smaller risks. Large quantities of fluid will only be released if the tanks are seriously damaged.

The sources of ignition are usually, exhaust from the engine, sparks from broken electrical equipment or leads, hot surfaces on the engine, and possibly sparks from the aeroplane sliding on the ground. The first two are likely to ignite the fuel direct. Oil is likely to ignite in contact with hot surfaces and this in turn may start a fuel fire.

The principal design features which assist in fire prevention are:—

(*a*) Tanks capable of standing very high impact loads.
(*b*) Tanks positioned so that failing structure is not likely to puncture them.
(*c*) Tanks and systems positioned as far as possible from sources of ignition, and also as far as possible from the occupants.
(*d*) Rendering inert and cooling the hot exhaust gases.
(*e*) Cooling hot engine surfaces and surrounding them with an inert atmosphere.
(*f*) Preventing continued pumping of fuel or oils.
(*g*) Preventing sparks in broken electrical circuits.

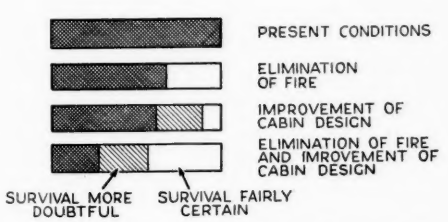

Fig. 14. Possible improvements in fatalities.

12. STRENGTH AND DESIGN OF TANKS

Considering first, normal tanks (metal or bag), it is questionable whether their resistance to bursting in crashes is as high as it could be. The elastic bag type of tank appeared to offer considerable advantages in taking the shock of the crash, but it is feared that economy of weight has often led to the use of wall thicknesses little greater than is required to contain the fuel in normal circumstances, and which is of reduced value in a crash. The importance of preventing the tank from bursting is shown by the following figures derived from an investigation made by the Accident Investigation Branch of a large number of crashes of multi-engined military aeroplanes. Major fires, as a percentage of all crashes, occurred as follows (*see also* Fig. 15):—

No fuel spilled	7%
Fuel spilled from broken pipe lines only	11%
Tanks burst	67%

The correlation between the occurrence of tank bursting and general damage to the aeroplane as a whole is shown by the following figures:—

	Serious damage	*Medium, light, or no obvious damage*
No fuel spilled	3%	56%
Lines broken	27%	26%
Tanks burst	70%	18%

The interesting point is that with severe damage, which was typified by the wings breaking off or the fuselage crushed as far back as the wing, 30 per cent. of the cases did not result in burst tanks. This suggests that with better tanks the frequency of bursting could be reduced, even when severe structural damage occurs.

With integral tanks, it is possible that careful location and design could provide safety as high as that of currently used lightly constructed bag tanks. If, however, the bag tanks were substantially improved, it is doubtful whether integral tanks could keep pace. The only answer then might lie in avoiding the use of integral tanks or using them only in the most carefully selected positions. In one American design it is claimed that the main box which comprises the integral tank in the wing is stronger under crash loads than the rest of the wing, so that the point of failure will be away from the tank. If this is practicable it is obviously a good feature.

So far as the position of tanks, whether normal or integral, is concerned the rules for good design are so obvious as to barely require stating. Tanks should not be installed:—

(*a*) in wing leading edges;
(*b*) in the fuselage—or if they must be in the fuselage—not in the forward portion;
(*c*) in the centre section or close to the engines.

This list does not leave much safe space to house fuel other than the outer wings. It has occasionally been suggested that wing tip tanks (*i.e.* the military drop tank) might be considered with advantage. This suggestion has two points in its favour. In a premeditated crash landing, a proportion of the fuel could literally be dropped at short notice, and in an unpremeditated crash the tanks might be torn away safely, or at least be as remote from the occupants as possible.

Other rather obvious points may be mentioned briefly. The array of pipe lines and pumps should be housed where least crash damage occurs and should be shielded from the ignition points. Failure of parts known to strike the ground first, landing gear or under surfaces of engines, should not cause disruption of the tanks.

13. "INERTING" AND COOLING HOT EXHAUST GASES AND SURFACES

It is usual British practice for piston engine installation to spray fire extinguisher fluid externally over hot portions of the engine and into the air intake. This fire extinguishant injected in the intake renders the exhaust gases safe by stopping combustion and by cooling the gases. Also the mixture of air, unburnt petrol, and fire extinguishant, quickly cools the exhaust pipes themselves, rendering them less likely to ignite oil, etc. The externally applied fire extinguishant temporarily provides an inert atmosphere surrounding the engine, and by the time this is dispersed, the engine will have cooled sufficiently for the risk of fire to be substantially reduced. In the past fire extinguishing equipment has largely been developed for extinguishing air fires, but latterly has been made to serve the second purpose of preventing crash fires. There is no statistical proof that the present equipment assists in preventing crash fires. The United States is conducting a large scale research, crashing

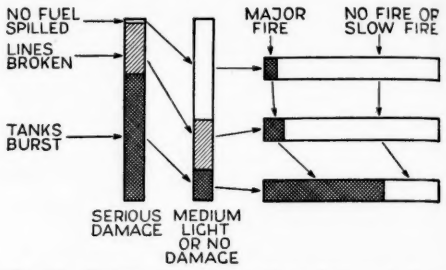

Fig. 15. Relationship of aeroplane damage to fuel system damage and outbreak of fire.

aeroplanes under controlled conditions, and the results of this work will be most useful. In the meantime, it is wise to continue to use and improve British practice. The essence of the solution lies in providing sufficient extinguishant to render the exhaust harmless and to provide an inert atmosphere, and to do this before the fire starts. It is doubtful whether present systems provide either sufficient quantities, or at a sufficient rate.

With pure jets the equivalent of the exhaust is so large that the quantities of extinguishant introduced into the intake would be out of the realms of possibility. Therefore the combustion must be stopped by turning off the high pressure cocks. It is believed that this causes very rapid cooling, as unburnt air sweeps through the tail pipe. It is also desirable to make the air in the jet pipe tunnel inert by a fire extinguisher spray.

14. PREVENTION OF CONTINUED PUMPING OF FLUIDS

In a propeller - driven aeroplane, the propeller itself is usually stopped by the crash. With a pure jet the cutting-off of the fuel supply is of assistance.

15. PREVENTION OF ELECTRIC SPARKS

Since electrical equipment or leads are almost certain to be severed in a crash, the main solution rests in the provision of a master switch which cuts off the electric supplies at the moment of impact.

16. CRASH-OPERATED SWITCHES

Many of the previously mentioned devices must rely for their operation on an automatic device triggered off by the crash itself. The

specification for such a switch is that it must always operate in a crash, but never otherwise. Most British aeroplanes embody an inertia-operated switch. Fear that this might operate when not intended, originally led to the use of insensitive switches, which served no purpose in moderate acceleration crashes. Later experience has made it possible to reduce the "*g*" at which the switch operates and by using two switches, both of which must operate before the other actions follow, inadvertent operation has been overcome. It is also modern practice to mount these inertia switches in a part of the structure which is likely to receive a severe jerk as soon as distortion or destruction of the under surface occurs. For some years other methods have been under development which, in principle, rely on structural damage to cause operation. It seems likely that frangible switches will eventually become a more reliable means of detecting a crash than switches which operate on inertia.

Crash switches are not fitted in American-built aeroplanes. There is a strong body of opinion which favours them in the United States, but the official U.S.A. view is to await the results of full-scale tests. Owing to the number of variables involved it is not possible to show whether the British use of the crash-switch has been beneficial. Since the weight penalty is small, and early objections to the dangers of such switches have been overcome, their use at present seems entirely justified. The author believes that full-scale tests will justify the crash switch and will promote development of more effective devices.

From the foregoing it seems that there is no revolutionary improvement in sight. Many features which have been mentioned are simply good modern practice. The value of others will be more completely understood when further full-scale experimental evidence is available.

17. SUMMARY OF CONCLUSIONS

1. While it is difficult to establish the level of safety at which to aim, substantial improvement in safety should be sought.
2. A review of accident causes does not suggest any easily achievable major reductions in accidents, but improvement in some directions offers considerable scope. In particular, in British operations, accidents in bad visibility deserve close attention, and the development of improved aids for navigation and approach should pay high dividends. The former will assist in preventing ditching accidents.
3. Everything possible should be done to reduce the load on the pilot. Simplification of controls of all kinds would probably assist.
4. So far as airworthiness is concerned, while a lack of this quality has rarely been the cause of accidents in past British operation, there are some indications of a rise in the figures and modern design trends are making the provision of adequate airworthiness increasingly difficult.
5. A radical reversion to the slower, simple, aeroplane of the past would no doubt solve many safety problems, but if this is incompatible with modern needs, improvements in airworthiness cannot be expected to produce material increases in the overall safety level. Instead, efforts will have to be made to avoid reduction. To a large extent prevention of a rise of accidents caused by lack of airworthiness will depend on foresight, attention to detail, rigorous testing, and so on. Such steps should not bear unduly hard on the economics of operation.
6. In the field of structural strength and performance the "cost" of airworthiness is high. Therefore, the previous satisfactory levels must be kept while avoiding undue penalty. This is gradually being achieved by closer matching of the aeroplane to the circumstances in which it flies.
7. The growing complexity of requirements is an inevitable result of the competing demands of increasing safety and increasing efficiency of the aeroplane as a vehicle. The growing complexity of the aeroplane provides so many potential danger points that requirements have become much more extensive.
8. The most fruitful field for improving safety, so far as the aeroplane itself is concerned, lies in making the aeroplane safe to crash. Specific suggestions for improvement are:—

Radical Changes

Design for low stalling speeds.

Design Changes

Fit backward-facing seats, or
Widely spaced forward-facing seats, or

Widely spaced alternately backward- and forward-facing seats, without fixed tables between.

Provide seats, belts, and floor structure giving 20 *g* protection in the aft compartment, and 10 *g* protection in the forward compartment.

Minimise the number of occupants of forward compartments.

Provide adequate padding on all objects in striking range which cannot be removed.

Use bag tanks in preference to integral tanks.

Use bag-type tanks capable of withstanding greater shock loads.

Development Work

Investigate the possibility of using wing-tip drop-tanks.

Increase knowledge of fire extinguishing methods specifically for crash use.

Investigate the best design of fuselage structure and seat design for absorbing shock loads.

APPENDIX

Table I shows numbers of accidents of different types divided between fully fatal, partly fatal, and non-fatal. The primary interest is in fatalities to persons but if used directly the fatality figures are likely to be misleading, as the inclusion of one or two accidents to large aircraft in a small sample will artificially boost the fatality figures in that sample.

It seems desirable therefore to use the proportions of accidents as a more reliable measure of the proportion of fatalities. To do this the partly fatal accidents must be taken into account. The device has therefore been used of counting the

"Equivalent" Number of fatal accidents as being the sum of

(Actual fully fatal accidents) + (Actual partly fatal accidents × proportion of fatalities in these accidents)

The resulting equivalent number of fatal accidents as a percentage of total accidents is then a reasonable measure of the fatality ratio.

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DISCUSSION

Dr. H. Roxbee Cox (Chief Scientist, Ministry of Fuel and Power, *Fellow*): Mr. Tye had made it clear that air travel was not the safest way of getting about, and the trouble was, as he had also made clear, that they were flying faster and faster. There was probably no possibility of aeroplanes flying slower and slower. Thus, as aeroplanes became faster and faster, not only must they be kept as safe as before, but they must be made safer still; and there was some evidence, in the curves shown in the paper, that this was being done. He was surprised to note that on the curves showing the relative accident rates between the United States lines and Great Britain's, the United States lines were the safer. Was there a general reason for that?

It was a little unfair to describe all those accidents involving human failures as being due to "pilot error." Sometimes accidents were due to human frailty, but how often were they due to the inadequacy of equipment on which the human element depended? There could be no more important study than that directed to making instruments reliable and easy to read, to making audible and visual warnings obtrusive and unambiguous, and to avoiding the curse of complexity. That did not apply to the instruments alone, but to the machine as a whole.

Sometimes simplicity seemed to be a thing of the past. When the first jet engines were made they had thought how delightfully simple and easy to control they were, and that in consequence they should make for the

greater safety of aeroplanes. That simplicity seemed to have been lost.

At the end of the section of the paper headed "Trends in Airworthiness Regulations" it was stated that there must be no hidden margins penalising 999 flights for the sake of the thousandth. That had puzzled him. He had thought that all regulations were in effect taking account of the thousandth case. If they could ignore the thousandth, they should be able to build far more economical aeroplanes. Certainly he had felt that in the past, when calculations were probably less precise than now, aeroplanes were probably often saved by the hidden margins. So that if they could find them—if they were not too well hidden—he would even now hesitate to get rid of them.

Under the heading "Broad or Detailed Requirements" the author had suggested there was a school of thought in favour of making requirements to ensure uniform economic penalty, and another concerned to establish a high and uniform safety standard. He thought there would be no doubt about the latter being the proper course, and he was very glad that it was the policy of the Air Registration Board always to work to it.

He believed it was true that the human frame could withstand very high g; but probably the function which they should really think about was $g\Delta t$, where Δt was the short time during which the g lasted. They could all withstand high g so long as they had not to withstand it for long.

He agreed that there was no real reason to suppose that passengers would not like backward-facing seats, so long as they were fitted in aeroplanes with nose-wheel undercarriages. With the old tail-wheel undercarriages, the passenger would find himself looking down hill while the aeroplane was on the ground. After all, many people preferred to travel in a train with their backs to the engine.

The advantages of the backward-facing seat were largely nullified, however, unless the fire risk could be reduced. If backward-facing seats were provided and the fire risk were eliminated they would apparently halve the fatality rate. When the gas turbine engine using kerosine—a "safety fuel"—was first coming into aircraft, it had been hoped that it would make a great difference to the fire risk; and he was still not convinced that it had not. Mr. Tye had said the evidence from most sources was that the safety fuel, kerosine, had not in fact resulted in a lower rate of fire hazard. From his own limited experience—he had unfortunately witnessed a few crashes—he thought that kerosine fires certainly were far less frightening, and where they occurred they seemed milder. If they could have backward-facing seats, fuel tanks at the wing tips, and a safety fuel such as kerosine, he believed there would be a large reduction in the fatality rate.

R. E. Hardingham (Air Registration Board, *Fellow*): It was perhaps surprising to see that, in Great Britain, 9 per cent. of the accidents were due to causes related to airworthiness. He was sure that Mr. Tye was not being sanctimonious about the British figure when he had compared it with the American figure of 29 per cent. Perhaps he would agree that the answer was that the present British register of aircraft included a number of American types which their American friends had developed for them, and which had flown for many hours before they were flown by British operators. By that he meant that troubles relating to lack of airworthiness on American-built four-engined transport aircraft had been experienced and rectified by the Americans before they had begun operations with the British-owned companies. Thus they had benefited by their experience.

They were now approaching a period when the first post-war designed British transport aeroplanes would be available and, with that in mind, they must be careful to ensure that the figure of 9 per cent. was not increased.

When such a large percentage of accidents was due to operational causes, it must be obvious to all that the greatest gain which could be made by aircraft designers was in the saving of life in an accident. It was fortunate that designers no longer refused to contemplate the possibility of their products crashing. He was sure Mr. Tye would agree that they were now receiving the greatest co-operation in the embodiment of safety measures such as crash fire precautions, adequate emergency exits, and so on. But they were not getting the support for backward-facing seats and for seating arrangements generally. It was time they stopped merely talking about it and really did something. From the report of the recent international meeting of operators it became clear that aircraft were to be converted for coach-type travel, which meant more seats for a given size of cabin; it seemed to him,

therefore, that the time was ripe for a real approach to the problem.

It had been said on many occasions that requirements and regulations tended to complicate aeroplanes; but he did not believe that. The travelling public had decided that they wanted to fly from London to New York non-stop, and the present complicated trans-Atlantic aeroplane was the result. He did not think the designer had much say in it.

Transport aeroplanes which would fly twice as fast and twice as high would soon be introduced, and bearing in mind the great demands now made on the skill and vigilance of crews, his worry was whether the future demands on them would become too great. All that the airworthiness authorities could do was to chase those problems with alleviation in mind, rather than cure; and that was what Mr. Tye and the Air Registration Board were trying to do.

H. H. Gardner (Assistant Chief Designer, Vickers-Armstrongs, Weybridge, *Fellow*): As one who had been associated with the Air Registration Board in the development of some of the requirements, he paid tribute to the logic and common sense which had been introduced right from the beginning. He felt that the Industry was whole-heartedly behind the A.R.B. in respect of the general basic requirements.

There were one or two matters, however, on which obviously there would be differences of opinion which it would take a long time to resolve. One which was always a source of argument was that of broad or detailed requirements. There was a difference between the international and the national type of regulation, and he put in a plea for the national requirements to be made as broad as possible because there was only one interpretation required, and the Board and its officials knew the sort of interpretation the Industry would give to those requirements. Internationally, however, there were two—not only the unknown of the personalities in connection with people's requirements, but also that of language. He felt that, so far as British requirements were concerned, the more detailed requirements which were gradually coming in brought a danger of standardisation, which was wrong.

They needed more information from the operators; statistics of aircraft operation would be invaluable as aeroplanes developed and their lives increased.

The problem of pilot error had always been a source of worry to all concerned, and he felt that the care with which the A.R.B. had dealt with the requirements which controlled the 9 per cent. of the accidents mentioned should at least be matched by those who were looking after operational requirements and all things associated with pilot error. He believed there was danger of the 9 per cent. increasing, because increased use would be made of instrument control such as, for example, the automatic pilot. Mistakes made by instruments would increase the errors attributed to the aircraft itself, and as things became more complicated, the danger would be increased.

With regard to performance and the new requirements which had to be prepared to meet the advances made in design, he urged the need for more information from operational trials before adopting requirements. In the past, the requirements were written before the new aircraft were available. The A.R.B. exercised the utmost restraint in introducing such requirements, but he did feel the need for detailed testing on the operational side. On the other hand, in any requirements there was always a need to get rid of a few obsolete ones, and that might be a matter for some investigation.

There was an impression abroad that designers did not like backward-facing seats. He did not think that was true; such seats were just as easy to design and fit as were the forward-facing seats, and it was really a question of pleasing the customer. If the customer wanted backward-facing seats he could have them; and if he wanted them to meet 15 *g* or 20 *g* accelerations he would have to pay for them. There was an economic level which to some extent fixed the degree of safety they could have, and although he saw no objection to the backward-facing seat, it could not be provided without considerable increase of aircraft weight. He felt that the figure of 15 lb. as the total weight increase involved per seat if they used 20 *g* seats was a little optimistic.

Group Captain W. K. Stewart: Sooner or later they would be forced to decide in favour of backward-facing seats; the problem would appear to be simply that with backward-facing seats the value of *g* and the rate of rise of *g* did not matter to the human body. He would prefer not to call them "backward-facing" seats, because the seats in R.A.F. Transport Command provided a

safety zone not merely against forward deceleration, but also against the other accelerations and decelerations that were experienced in a crash. They knew of the many injuries that people could suffer from lateral acceleration, including those due to things falling from luggage racks, and so on, and to contact with the racks.

On the other hand, he believed it was true —and Mr. Tye had emphasised it—that the safety belt did not cause major injury to the individual. Much had been written in the newspapers, including the medical press, lately about post-mortem findings on victims, and it was felt that quite a lot of the injuries sustained were not concerned with the fact that the body would "jack-knife" over a safety belt; when wearing a safety belt the body could sustain a fairly heavy load without risk of internal injury. It was not known, however, whether the sudden release of pressure, as when a heavy load was imposed on the body and the safety belt parted, might cause injury.

The mixture of forward- and backward-facing seats, with tables in between, multiplied pre-crash drill; and he was not generally in favour of pre-crash drills where there was a large number of passengers. But the table then served in the same way as did the knees of the passenger opposite in relation to facial and skull injuries.

P. G. Masefield (Chief Executive, British European Airways, *Fellow*): Every airline operator endeavoured day and night to ensure the maintenance of the highest standard of safety which equipment and the most up-to-date techniques allowed him to achieve. But the subject was so "red hot" that airline operators did not advertise safety, although some might well do so.

He hoped he would not be regarded as being cynical in saying that the word "crash-worthiness" was terrible. He did not think anything could be "worthy" of a crash, nor did he think that they should design for a crash; they should design to avoid them.

The primary emphasis should be on doing everything possible to avoid accidents. In B.E.A. they were making a comparative performance test of every individual aeroplane after major overhaul. It was only by making continuous comparative tests on every aeroplane in a fleet, and by proper calibration of them, that they could ensure that the performance of a large number of similar types of aeroplanes was maintained at a level.

A large airline must be proportionately safer than a small one, for there was greater exposure to the risk of accidents in an organisation which was doing a lot more flying than another. Bearing in mind such intangible factors as public reaction and opinion, a large airline could not afford to have a greater number of accidents in a given period than could a small one. The predominant query which arose in the public mind was "how *often* do accidents occur?" —not how many miles were flown between accidents.

He did not wish to create the impression that he was against backward-facing seats; indeed, B.E.A. was the only airline in the world having an aircraft with 40 per cent. of its seats facing backwards, and they were getting some interesting passenger reactions already. But he did not know of any scientific problem on which so far technicians had rushed into print more quickly, and with less real evidence, than on the subject of backward-facing seats. R.A.F. Transport Command had some evidence, but it was not conclusive and there had been some wishful thinking about it. He urged that they really establish all the facts before making up their minds. In B.E.A. and B.O.A.C. they were working on the problem and making tests, and the evidence so far was that it was possible to make forward-facing seats as safe as the backward-facing ones.

All sorts of difficult problems were encountered, one being that, when analysing accidents, it was found that there was not a high proportion of the type of accident in which the backward-facing seat would be considered of advantage, *i.e.* the symmetrical accident. Where an aeroplane did not crash straight ahead, but, for example, turned round sideways, the backward-facing seat was to all intents and purposes equal to the forward-facing seat. There had been a mishap during training, when an aeroplane had skidded round at 50 m.p.h. after landing, and had proceeded backwards into an obstacle. The crew were in the front and they had fetched up, in effect, sitting in backward-facing seats.

B.E.A. had had a little experience of flying the "Elizabeth" class aeroplane, in which 40 per cent. of the seats faced backwards. Comments cards were supplied to the passengers in order to obtain their views,

and it was interesting—and a little surprising—that quite a percentage objected to backward-facing seats. A reason was that that aeroplane climbed at a fairly steep angle, so that the floor had a considerable slope, with the result that for about 20 minutes, during the climb to an altitude of something like 15,000 ft., those in the backward-facing seats were leaning forward. If the aircraft were operating on a fairly short run, such as that between London and Paris, when meals were being served for almost the whole time of the flight, it was rather annoying to have the food slipping off the farther edge of the table! It was much easier for it to fall into one's lap! That was a perfectly serious point which was noted on the comments cards quite often.

The problem was one on which B.E.A. would like the help of the A.R.B. and Transport Command. It was not one on which B.E.A. had any fixed ideas. But they wanted to be forward-looking in their approach.

If air transport were not the safest way of getting about, at least it was not the most dangerous. In the end the helicopter might turn out to be one of the safest forms of transport, because it could land at low speed in bad weather.

In the airline business there was no complacency. In order to avoid accidents they wanted all the information they could find, in order to arrive at the right answers to the problems which Mr. Tye had put forward.

J. D. North (Boulton Paul Aircraft Ltd., *Fellow*) *contributed*: His remarks were purely personal and not made as a member of the Air Registration Board.

It would be well worth while to have a number of design studies prepared in which the various points to which the lecturer had drawn attention were pursued and perhaps extended. At first sight such designs might seem to be unacceptable to operators, but further reflection might suggest that they had a great deal of merit. Backward-facing seats in aircraft were not new; in fact on many classes of civil aircraft they had been quite common and he had never observed any particular objection to the taking of backward-facing seats.

Figure 1 showed a considerable difference between the U.S.A. and U.K. fatality rates. Part, at least, of the possible explanation might be due to the fact that the average terrain for U.K. operations was much less favourable than that for the U.S.A. He believed that at one time American domestic airlines showed much more favourable results than their overseas airlines.

This difference in the accident rates ought to be reflected in the height of the diagrams on the right of Fig. 3. If this were done it would be found that the fatality rate on a mileage basis due to airworthiness deficiencies was actually rather higher in the U.K. than in the U.S.A.; the *percentage reduction* was merely due to an excess of other kinds of accidents.

The statistical methods to which the lecturer referred were open to considerable objection because they contained a number of unjustified and, in his view, unjustifiable assumptions either explicit or implicit. In matters of this kind which involved mixed statistical and technical considerations the statistician easily thought that the assumption was justified on technical grounds, while the technician believed them to be justified on statistical grounds. Mr. Tye said "It may be noted that one person in 1,000 dies accidentally each year in the U.S.A. and this gives a point to the order of risk which is accepted with equanimity." Equanimity was an individual characteristic and the individual person was interested in his personal risk and not in the average risk over the population. Mr. Tye suggested that a set of rules should ensure reasonable equity and likened this to the rules of a game which were necessary for the enjoyment of the player.

However, the rules which governed the behaviour of man as a social animal were not artificially constructed to provide an enjoyable game. They were necessary to make life possible in a society and in this country those rules were embodied in the common law. A relevant extract from Holland's "Jurisprudence" was: "Results may also follow from acts without being intended. Such results, if the person acting had no means of foreseeing them, are ascribed to 'chance' and no responsibility attaches to him in respect of them. If they are such as he might have foreseen had he taken more pains to inform his mind before coming to a decision they are attributed to his 'negligence.'" The obligation of those responsible for air transport was so to inform their minds that all reasonable steps had been taken to protect the individual traveller, *i.e.* what was required was to put a ceiling on the *individual* risk rate and not to maintain an average. Proposals such as

declared temperature, for example, on the basis on which it was proposed to be calculated did not satisfy the requirements of the quoted rule of jurisprudence.

The distribution of rate of climb shown in the histogram of Fig. 4 could only be transformed at some chosen significant level into a probability on the assumption that it related to some randomly selected aircraft on a randomly selected occasion. Probability meant nothing apart from the evidence upon which it was based and the evidence available relating to a particular aircraft on a particular flight would lead to a quite different probability distribution. It was important moreover to remember that the risk ceiling related to the total risk and as between one aircraft and another, acceptable numerical values could not be assigned to individual elements unless the elements were identical and equally correlated. He thought it was not impossible that it was a failure to appreciate those points which led to the very demand which the lecturer deprecated, namely equality in payload. He would, however, fully support Mr. Tye in his statement that the risk ceiling could only be settled by a balance between safety and economics. A logical consequence of this was that the risk ceiling was not necessarily fixed as between one aircraft and another or even one route and another. What was to be regulated was the minimum utility (in the strict meaning which it had in economics) and the balance could only be exhibited as iso-utilities by the technique of indifference relations.

E. R. Stables (Royal Aircraft Establishment, *Assoc. Fellow*) *contributed*: He agreed with Dr. Roxbee Cox that paraffin was better than petrol in a crash fire; the rate of spread of fire was appreciably less than with petrol, and the risk of a re-strike of fire on an area already extinguished by a tender was also much less. Those characteristics might sometimes make all the difference between passengers' escape or disaster.

On British experience with fire protection devices, on current developments and on future trends, he agreed with everything Mr. Tye had said and thought that the effort being expended in Great Britain on investigating the possibilities of reducing the fire risk further was satisfactory, except perhaps in regard to crash fires.

On page 95 it was stated that a radical reversion to the slower, simple aeroplane would solve many safety problems. No one seemed to want to consider this course very seriously, and yet it seemed to be the one which promised by far the best results. Had they not enough courage to take a step backward even when they were pretty sure that a step back was the sensible thing to do? He was pleased to hear Mr. J. D. North advocate design studies to the limit of Mr. Tye's suggestion, and hoped he would include a study of a modern "slower and simpler" aircraft. Might not such an aircraft be more economical and more comfortable? He wondered whether the public really did demand higher speeds, higher altitudes and bigger aeroplanes.

There seemed to him to be enough common sense in the slower, simpler aircraft suggestion to warrant an attempt to strengthen the case for such a policy, on statistical grounds. It was said that statistics could be made to prove anything.

On page 75 Mr. Tye said that in America one person in every thousand died each year from accidents of all causes. This, he thought, neglecting all other forms of meeting one's end; meant an average expectation of life of 1,000 years. If road accidents were considered as the only cause of death it was seen that the expectation of life was 10,000 years. Either figure seemed highly satisfactory, or very depressing, according to one's outlook.

But for the aircraft figures the picture was very different. Using Fig. 1 as the basis, assume that in the not too distant future business men might use high speed aircraft for the same periods of time that many now spent in trains or buses, say, 2 hours per day for 200 days per year. The average expectation of life, neglecting all other causes of death, worked out at about 120 years. At first sight this might appear good enough, but if they then considered that the business man might travel in, say, a 20-seater aircraft they concluded that he would be involved in an accident in which one person was killed, every 6 years. The outlook began to look gloomy. If they thought of the possibility of some of the remaining 19 passengers being injured they might become really depressed. As for the regular air crews, it would seem that there was every justification for their having a good time while they could!

It seemed to him that they must logically come to the conclusion that they should not accept the present situation; the air risks

were far in excess of those of other forms of public transport, especially on a basis of time spent in them, and therefore there would seem to be no excuse for not investigating very thoroughly what appeared so clearly to be the most effective means for improvement. He thought that if the public appreciated the reasons they would support such a move.

E. N. B. Bentley (Chief Technician, Percival Aircraft Ltd., *Assoc. Fellow*) *contributed*: The opinions expressed were his own and not necessarily those of Percival Aircraft Ltd.

He did not agree with Mr. Tye's implication that the attempt by the U.S.A. to reduce stalling speeds tended to prohibit development. Mr. Tye himself pointed out the great increase in safety that could be obtained by a reduction in stalling speed and insistence upon this at the time of the American request might have brought about a really worthwhile development in transport aircraft. After all it was not very clever to increase the cruising speed of aircraft by 50 per cent. if the stalling speed also went up in the same proportion. If a low stalling speed had been insisted upon, manufacturers would have been forced to develop slots, flaps, variable incidence wings, and so on, in order to achieve a safe and reasonable stalling speed without unduly sacrificing the cruising speed.

He fully agreed with the desirability of backward-facing seats and with Mr. Gardner's statement that the Industry would provide them *when they were asked to.* His Company had already been asked to do so by the R.A.F. and it seemed rather strange that the Services, who were generally prepared to accept somewhat higher risks than civil operators, were so far the only customers who had asked for such seats. Mr. Tye's estimate of a 15 lb. increase in weight for a 20 *g* seat was far in excess of what they knew they could achieve on small aircraft. They had designed, and were about to test, a 25 *g* backward-facing, fully-adjustable seat which was expected to weigh not more than 6 lb. in excess of the weight of a 6 *g* seat. As most of the increase in weight in the more luxurious seats used by the Corporations was in upholstery, it seemed that the increase in the structure weight of such seats need not be a great deal more than the figure he had quoted.

Was it not possible, at any rate on aircraft of moderate size and performance, to reduce the vast amount of office work needed to prove compliance with airworthiness requirements? Aileron stressing, for example; before the war loading requirements for an aileron could be worked out by a relatively junior stressman in perhaps half a day. Present-day requirements needed an experienced aerodynamicist who would probably need the best part of a working week to do the job. He questioned whether all this extra labour had achieved any useful result; were ailerons any safer than they used to be? There was a serious shortage of manpower on the design side and, while this was largely due to the extra complexity of the aircraft, a considerable part was also due to the complexity of the airworthiness requirements. Any possible reduction in this work would do much to relieve a serious bottleneck in the design office work.

H. J. Crampton (*Associate Fellow*) *contributed*: Mr. Tye had postulated the alternatives "equal airworthiness" and "uniform economic penalty," but no real choice existed because the first was the *sine qua non* of any Airworthiness Authority—and the second was an inescapable principle which would compel recognition, either in the formulation of the requirements or in the granting of concessions. It was surely true to say that this inevitability was already responsible in a large measure for the degree of detail in existing requirements due to the fact that, insofar as designers were granted a say in their formulation, they were constantly on the watch for proposals which were unjustifiable on the grounds of economic cost, *i.e.* weight. Since they could rarely reject a proposal as entirely unnecessary, they must adopt the alternative of eliminating all hidden margins, which process led directly to making cases fit the physical facts as closely as possible in all normal and individual cases. This could only be done by refinement in detail.

This position all too often presented the designer as a heartless rogue who would buy success at the cost of human life. In reality he was merely very sensitive to the fact that, the payload of an aircraft being a regrettably small proportion of the total weight, it was critically affected by the severity of the requirements, and conversely that a handsome increase in the former might often be secured at no real sacrifice in safety.

Thus, once requirements went beyond the mere statement of principle, they were driven to more and more detail, as was happening

This all added to administrative inconvenience, perhaps, but was it really such a bad thing as they sometimes supposed? Did it really make things more difficult for the designer? The probability was that it did not, because the same economic pressure which in fact compelled detail of requirement would demand detail of *application* in any event. In other words, the requirements did not impose any complexity on the business of designing an aircraft, they merely reflected it.

Suppose that the requirements did revert to statement of principle only. To produce an aircraft at once safe and competitive—and only a safe aircraft would be competitive in the long run—a designer must examine his exceedingly complex product in extreme detail—often in much more detail even than the requirements suggested—and in a large variety of conditions. Nothing therefore would be saved. On the other hand, how would compliance be established? Of what use would the I.C.A.O. "hallmark" be without a book of rules in detail which indicated what everyone meant by an acceptable minimum of safety?

If they wanted a uniformly high standard of airworthiness they must accept an Airworthiness Authority whose business it would be to make regulations. Economic pressure would insist that they endeavoured to secure safety without prohibitive cost in operation, and detailed requirements became inevitable. The degree of detail would reflect, and not control, the complexity of the analyses and tests applied by the designer.

This being so, they should not so much be concerned to banish detail from the requirements as to check unnecessary triviality, to eliminate textbook platitudes, to promote intelligibility and ease of reference, and to secure more uniformity in the degree of detail employed. In this respect, current requirements were open to serious objection. The lack of facts and data, to which Mr. Tye had referred, had led to a situation where many important requirements appeared to be detailed in such a manner as to secure uniformity of interpretation, but which in reality were not so because they were overlaid with some general and ill defined provisions. Prominent examples of this were the Gust and Landing requirements which were subject to the provision that, "where the structural flexibility is such that any rate of load application, likely to occur in operating conditions corresponding to a specified load, can produce transient stresses appreciably higher than the stresses corresponding to static loads, the effects of such rate of application should be taken into account." This innocent looking recommendation implied an additional factor of anything up to 2.0, made nonsense of the apparent preciseness with which the case proper was invested, and put an unwarranted premium on the honesty of the designer. If sufficient information were available to enable an interpretation to be made, then it should be used to make the recommendation into a further detail of the requirement; if not, then the recommendation should either be discarded as useless, or an arbitrary addition to the basic requirement made if considerations of safety demanded it.

An even closer association was needed between the technicians who wrote, and those who applied the requirements.

D. J. Lambert (Vickers-Armstrongs Ltd., Weybridge, *Associate Fellow*), *contributed*: Mr. Tye suggested that the structural requirements had been rationalised fully within the limits of the available data. Had enough been done with the material at their command? What was being done to collect more data? Perhaps it was an erroneous impression but it did seem as if the U.S.A. was much more conscious of the importance of research into the phenomena causing design stressing loads than they were in Great Britain. In particular this applied to gust research and to manœuvre load research. He did not belittle the efforts in this country of Dr. Hislop and Mr. Czaykowski respectively in those two fields but he did not think that they had really got down to those problems, particularly on the civil side.

The principles embodied in the performance requirements had resulted from some 28 full day meetings of a committee of 10 or 12 people drawn from the various interested parties. In addition much more work had gone on behind the scenes and in international meetings. Could it honestly be said that similar effort had been, or was being, expended on the civil structural design requirements?

Mr. Tye had cited as an example of "requirements which have been materially altered" during the rationalisation process, landing gear strength requirements. Perhaps those were more rational than they were, but as an example of their failings chapter D3-5 suggested that for all the landing cases the

wing lift be assumed equal to the aircraft weight. That was, in both nose up and nose down attitudes the lift should be considered the same (a dubious assumption inadequately justified by the differing flight paths implied by the different velocities of descent) and no allowance was recommended either for the tail load which might be high, due to the large ΔC_{M_0} of many high lift flaps, or for the tailplane couple which, due to the large elevator angles often used in landing, might also be significant. Having regard to the importance of the landing cases in many fuselage designs it seemed unlikely that the cases had been rationalised adequately or to the extent of their knowledge. This was not the only example which could be quoted.

The statistical approach to performance requirements had met with wide international approval and it was suggested in the paper that the Board would be willing to recast its structural requirements on a probability basis. Remembering the results of the calculations on "Take-off field length required" in which a factor of 0.95 was found to be applicable to the Engine failure Start-Stop distance of twin-engined aircraft, would Mr. Tye agree that by similar methods of calculation, take-off weights, say 5 per cent above the basic structural design figure, might be arrived at and be statistically justifiable? If this were so then it was high time an enthusiastic and energetic attempt was made at infusing probability into structural design requirements.

It was unfortunate that the suggestions made on crashworthiness tended in one respect at least to clash with accepted and even fundamental design requirements for future aircraft. That was, modern swept aircraft generally required fuselages with much of their length forward of the wings for c.g. reasons. In addition, most designers strove to keep all their passengers forward of the jet pipes on jet aircraft, and with conventionally mounted engines this also tended to move the passengers to the positions indicated by Mr. Tye to be most dangerous. An example of this tendency was seen in the Lockheed L193 four-jet project in which some two thirds of the passengers were seated forward of the front spar. While agreeing with Mr. Tye's conclusions on what was advisable, he felt that the achievement of that ideal would be extremely difficult.

Wing Commander G. P. Gibson (*Assoc. Fellow*), *contributed*: A good part of the lecture was devoted to the crash aspect and a case was made out for the best place to sit in an aircraft in the event of a crash. Such melancholy design features might be of some interest to the passenger but they could hardly encourage him to travel by air.

If the paper were directed to the operator and designer then they had a great deal of their attention focused on the result of crashes. If they went off to design and operate according to those influences then he thought they would be tackling the problem from the wrong end. Surely the design and operation should be such that crashes did not occur? That was better than starting with the assumption that there would be a crash.

Had the lecture been on modern trends in rail (or ship, motor, stage coach) requirements it would be unlikely that so much attention would be devoted to where the passenger sat or which way he faced. The mere suggestion that the first third of the vehicle or ship was lethal would damn it forever.

He felt that the real problem centred around one word—reliability. By that he meant that the aircraft could be depended upon to carry out its job under all conditions (or variables) to which it would be subjected. There were many variables upon which a flight from A to B depended. The aircraft, the crew, operator and ground services all played their part; sometimes the unruly passenger or the explosive freight could also be of influence.

Confining these remarks to the aircraft there were still a number of variables which would affect the flight such as proper design and works inspections, susceptibility to heat, cold, fatigue, and mechanical wear, to mention only a few. The de-icer that did not de-ice, the windscreen wiper that did not wipe, the indicator that did not indicate—as often as not it was factors such as those that caused disaster, and it was on this aspect that designers of aircraft, engines and equipment should concentrate.

The airworthiness requirement should be "Reliability."

G. Korab Rulikowski (*Assoc. Fellow*) *contributed*: The backward-facing seat was often condemned on the grounds that it put the passenger in an uncomfortable position during a prolonged climbing flight. This objection seemed to prove only that the design of the present backward-facing seat was not correct, but in his opinion, no seats

were designed correctly. All were of the "tall" type which forced the leg to make 90 degrees with the thighs, and had a bad effect on blood circulation. A sailplane low "floor level" seat allowing the legs to be outstretched (almost 160 degrees between legs and thighs) seemed to be best from all points of view. When the aeroplane was climbing, the passenger would balance his body on adjustable foot rests. An adjustable foot rest for a tall type of seat would result only in making the angle between the legs and thighs more acute in the climbing position than it already was and the passenger, with or without foot foot rest, would slide out of the seat. In a "floor type" of seat it was easy to balance against a foot rest during any climbing flight.

There was, however, a drawback for this type of seat; it required twice as much leg room in front of it. To counteract this he had built in the backward-facing seats of the "Whale" (an aeroplane project intended as a Rapide replacement and semi-cargo aeroplane) in a semi-double-decker fuselage. There were two superimposed semi-decks on each side of the fuselage, with one common corridor in the middle and each semi-deck had one row of "floor-type" backward-facing seats. The section of the fuselage was a compromise between a full double-decker and a single-decker fuselage and allowed for the same number of passengers to be accommodated as the equivalent single decker. The passenger cabin was behind the cloakroom, kitchenette and freight compartments, which were specially stretched and considered to be effective crash shock absorbers. There were no compartments aft of the passenger cabin and the normal access door was in the front of the fuselage.

G. Ratcliffe (*Graduate*) *contributed*: The arguments as to whether or not civil transport aircraft should be fitted with high "*g*" rearward-facing seats appeared to be affected not only by the safety of the passengers but by operating economics.

To obtain a degree of safety on the forward-facing seat comparable with that on the rearward-facing type it appeared that a 50 in. seat pitch was required. This was greater even than that used on the Hermes 4 (46 in.) which was regarded as luxury standard. Such a condition represented in this case 8 per cent. loss in volumetric payload, *i.e.* on the basis of the 165 lb. +66 lb. = 231 lb. passenger, a loss equivalent to 18.5 lb. Even so, the "jack knifing" of passengers could still be dangerous if an item of luggage or cabin equipment, such as a seat tray, were interposed between a passenger and the seat in front.

Seat inclination could be adjusted to remedy the complaint of "downhill" effect with rearward-facing seats. The two types on which present operational experience was based were both tail wheel aircraft (Hastings and Valetta).

The weight penalty need not be as great as the 15 lb./passenger quoted. An analysis of the problem had been made by Handley Page Ltd. and this had shown that with a little careful design in the placing of the seats relative to floor beams a satisfactory compromise on floor strength could be obtained. In fact the penalty on floor weight had been found to be zero for strength up to 15 *g* when due consideration had been given to normal walking loads, etc. For 20 *g* the corresponding figure was about 4.5 lb./passenger. As pointed out by Mr. Tye the crash causing accelerations greater than 20 *g* was rare and this figure was probably the optimum when all aspects were taken into consideration.

Provided that certain rules about the general layout of the seat were accepted for structural considerations, *i.e.* good triangulation, etc., the increase in weight need not be

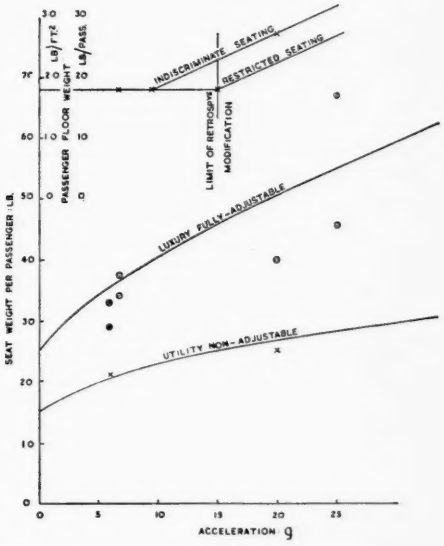

Fig. A.

greater than 2 lb./seat relative to the normal type at present in use. The low figure was partly due to the facts (*a*) that a large part of the weight of a seat went into the upholstery and adjusting mechanism and (*b*) that the requirements for present-day seats did not justify any great consideration to structural efficiency.

Practical examples of proved seat weights were the Hermes 4 6 *g* seat at 38 lb. and the Hastings 4 20 *g* rearward-facing V.I.P. seat at 40 lb. The overall picture showing seat and floor weights was given in Fig. A.

When all these points were taken into consideration for a chosen standard of safety and an average medium range case, *i.e.* with space limited payload the overall loss in payload for the 20 *g* case was:

Forward-facing $18.5+4.5+2=25$ lb./passenger

Rearward-facing $4.5+2=6.5$ lb./passenger

The effect on weight of the actual process of turning the seat round had been ignored as it was of negligible proportions*.

MR. TYE

Some of the matters dealt with in the lecture had been discussed by several speakers.

He had failed to trace the underlying reason for the higher accident rate in British operations compared with that of U.S.A. It might, as suggested by Mr. North, be connected with the nature of the terrain overflown; another possibility was the weather.

A number of speakers had referred to the undesirable trend towards an increasing array of controls, instruments, and so on, with the consequent increasing demands on the pilot. He thought it important that the engineer should become closely acquainted with the lessons the physiologist and psychologist could teach him. If in future they were to provide protection against the so-called pilot error, a much better understanding of the relation of the man to the machine was essential.

He was glad that certain speakers were inclined to disbelieve the disappointing statistics which had tended to show kerosine to be as great a risk in a crash as petrol. He himself felt that, while the figures had been carefully examined so as to obtain as reliable guidance as possible, there remained an element of doubt in that other factors might have influenced the results. He felt that while they should not rely on kerosine as being the ready-made answer to fire risk, they could continue to hope it would be beneficial.

He was grateful to contributors who had submitted results of design studies on the weight penalty associated with higher strength seats. Those of Mr. Ratcliffe (6.5 lb./passenger for an increase from 6*g* to 20*g*) and Mr. Bentley (6 lb./passenger for an increase from 6*g* to 25*g* for the seat itself) were very encouraging. They bore out the usual experience that the designers ingenuity produced more palatable results than were first anticipated.

Dr. Roxbee Cox: The point he had tried to make, perhaps obscurely, on "hidden margins," was that with arbitrary requirements, on most flights margins were provided which were higher than necessary for safety, but which ate into payload. The more closely the requirements reflected the operational conditions prevailing in a particular flight, the smaller the hidden margin became, without detriment to safety, and with benefit to payload.

Mr. Hardingham: There was no doubt that because there were several American types in British service, and because these types had experienced troubles (which had then been rectified) during their earlier life in U.S.A., they had been protected from many accidents. He agreed that there was no cause for complacency about airworthiness of British aircraft; the true test would come soon, with the introduction of new British types.

The reference to coach-type seats was opportune. This particular trend was liable to increase crash risks, and it made a concerted attack on the problem of cabin arrangement even more urgent.

Mr. Gardner: He agreed about the general principle of seeking broad, rather than detailed, requirements, but it was important that "breadth" should not be synonymous with "looseness." A loose requirement invited wide variations in the level of airworthiness achieved. It had frequently seemed that detail had crept into the code of

*R. S. Stafford—Discussion on Air Travel from the Passenger's Point of View. *Journal R.Ae.S.* September 1951. p. 557.

requirements due to the difficulty of specifying the principle of what should be achieved sufficiently precisely by any other means. A difficulty about "broadening" national requirements, while accepting a detailed international code, would arise if and when the I.C.A.O. Standards became mandatory.

The need for the most careful "testing" of proposed requirements—as had been done in respect of performance—was fully accepted. Perhaps a good feature of the international debates had been the need to justify every step before any existing requirement could be replaced.

Group Captain Stewart: As one who had devoted much time to the medical aspects of crash risks, Group Captain Stewart's remarks were most helpful. The possibility that the sudden release of pressure on the body when a safety belt broke might cause injury was new to the lecturer. If this proved to be the case, it would be another factor disposing towards a preference for backward-facing seats. While the presence of a table between seats facing each other provided an unnecessary additional risk, without a table the spacing between the seats might be such that the knees of the passenger opposite were clear of the head of forward-facing passengers.

Mr. Masefield: The remark that a large airline must be safer than a small one, because of the public reaction to too frequent an association of an accident with a particular airline, was interesting. The whole question of what degree of safety the public wanted was exceptionally difficult and if the lecture provoked more thought, a useful purpose would be served.

He was glad to hear of the interest which B.E.A. were taking in seating arrangement matters, and in particular their quest for information for passengers flying in the backward-facing seats in the Elizabethan class aeroplane. Mr. Masefield's view that backward-facing seats were only of value in a "symmetrical" crash was open to dispute. So far as one could foresee in crashes with some yaw and sideways sliding, the backward seat would have advantages.

It was hardly correct to suggest that technicians had rushed into print so very quickly on this subject. Over ten years had elapsed since Mr. Pekarek, then of the R.A.E., had advocated improvements in seating arrangement, including facing backwards.

Mr. North: It was true, as Mr. North said, that accidents associated with lack of airworthiness, when expressed as a rate per 10^6 aircraft miles, were of the same order in U.K. and U.S.A. operation. The small percentage of airworthiness-caused accidents in the U.K. could therefore be accounted for as arising solely from a high rate of operationally-caused and other accidents. He felt, however, that the details of the actual accidents should be examined as the numerical answers might possibly mislead. When this was done, it was clear that U.K. operation had been very free from some airworthiness-caused accidents of a kind experienced in the U.S.A.

He hesitated to debate the subject of statistical methods, realising the depth of the water in which one would rapidly find oneself. In quoting a figure of one person in 1,000 dying accidentally as a clue to the level of risk accepted with equanimity, he had in mind only the very general order. For instance, if there were one accidental death per ten persons per annum, the public would almost certainly rise up against the system which led to such danger.

Mr. Stables: Although Mr. Stables' method of presenting expectation of life figures might be debated by the statistician, he accepted them as a striking way of illustrating the level of risk in flying. The plea for slower and simpler aircraft could not be too heavily underlined.

Acceptance of moderate speeds would help towards a reversion to simplicity. This in turn should reduce the frequency of accidents, and when the accident occurred the chance of escape was better. On some routes, *e.g.* the trans-oceanic ones, speed was essential; but on short inter-city routes the slower aeroplane might well offer all the passenger wanted, with benefits to safety and economy.

Mr. Bentley: The point that a limitation on stalling speed was not a prohibition on development, was a good one. He feared that most designers in the past would have resisted a limitation on stalling speed. But with a growing realisation of the consequences, it was to be hoped that designers would tackle the problem without legislation.

Mr. Bentley had made a case for requirements to be written in a form needing less office work to show compliance. Broadly, there were the extremes of basic requirements which entailed considerable office work, but

which should give the lowest weight for given strength, or more simple arbitrary requirements which sacrificed a little structural efficiency. The problem was to establish a reasonable compromise, and possibly the compromise differed according to the class of aeroplane that was being considered. Perhaps present requirements suffered from having been drawn up primarily with the large aeroplanes in mind.

Mr. Crampton: The contributions of three designers indicated the difficulty of the airworthiness authority. Mr. Crampton considered detailed requirements as almost an essential, Mr. Gardner pleaded for basic requirements, while Mr. Bentley felt that simple cases were necessary. Possibly the final answer would be to prepare separate codes for large complex aeroplanes and small simple ones. For the large aeroplanes the requirements should be expressed in basic terms, but could be supplemented by detailed matter which would give a closer definition of the intended safety level. Provided that the designer was free to vary from the detailed material, the objection to unnecessary steering of design should be overcome.

Mr. Crampton's criticism of the inclusion of vague phrases was accepted. Usually they sprang from sheer lack of data, or of time to interpret available data.

Mr. Lambert: A major effort—such as had been devoted to performance—might improve structural requirements, but he felt that such improvement would be severely limited by sheer lack of data. A committee had been formed not long ago to review landing gear strength requirements, but its work was seriously hampered by the absence of loading statistics. The smallness of the effort to remedy this lack of data was disturbing. It seemed a curious thing that much research was devoted to stressing methods but little to the externally applied loads. One of the weaknesses was the shortage of recording instruments, suitable for use in operational aeroplanes. There had been a demand for them for years, but their development was extremely slow.

Wing Commander Gibson: He had hoped that the day was past when anyone would advance the view that " aeroplanes must be designed to fly—not to crash," but that, in effect, was Wing Commander Gibson's theme. Certainly they must design aeroplanes with the object of preventing crashes; that was what the designers had been doing since the beginning. But it was all too clear that the degree of success was, and was likely to remain, only partial. Would Wing Commander Gibson object to designing cars with safety glass screens and rear fuel tanks?

Mr. Korab Rulikowski: The project described was interesting. It suffered from the disadvantage that the passengers, particularly those on the upper deck, might feel somewhat constricted. There were several possible ways of improving the risks in a crash, and in the end it would be for the public to select what they felt to be the best compromise between comfort, crashworthiness, and costs.

Mr. Ratcliffe: He was grateful for the data submitted by Mr. Ratcliffe on the weights of seats and floor structure associated with various values of " g." The figures were encouraging. The suggestion for expressing in terms of loss of passenger load the " lost space " arising from adequate spacing of forward-facing seats, indicated in a convincing way the value of simply turning seats round and retaining closer spacing.

*A Shortened Method for the Calculation of Aerofoil Profile Drag**

by

E. M. DOWLEN, D.L.C., D.C.Ae., Grad.R.Ae.S.

SUMMARY

A rapid method is developed for estimating the profile drag of an aerofoil with a known transition point position. The results are in good agreement with previous calculations.

1. INTRODUCTION

The method of estimation of aerofoil profile drag suggested in 1937 by Squire and Young[1] involves the step-by-step solution of boundary layer equations along the surface of the wing.

Suggestions for reducing these calculations to the evaluation of one or more direct integrals have been made by Tetervin[2] for the turbulent boundary layer, and by Young[3] for the laminar layer.

A combination of these two shortened methods leads to an expression for the profile drag which itself may be considerably simplified with no appreciable loss of accuracy.

The time required for the estimation of aerofoil profile drag is thereby reduced to a few minutes.

NOTATION

"T.E." refers to conditions at the trailing edge.
"T.P." refers to conditions at the transition point.

c	aerofoil chord
x	distance along chord
s	distance along surface
C_D	drag coefficient
C_{D_0}	profile drag coefficient
u	local velocity inside boundary layer
U	local velocity outside boundary layer
U_0	free stream velocity
ν	kinematic viscosity
θ	momentum thickness $= \int_0^\infty \frac{u}{U}\left(1-\frac{u}{U}\right)dy$
H	ratio of boundary layer displacement thickness to boundary layer momentum thickness
R	aerofoil Reynolds number $= U_0 c/\nu$

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*An extract from College of Aeronautics Report No. 35.

R_θ momentum thickness Reynolds number $= U_0\theta/\nu$
R_{θ_1} momentum thickness Reynolds number at transition
k, n constants in the equation $\tau_0/(\rho U_0^2) = k/R^n$ for skin friction coefficient
b $(1+n)k/R^n$
p correction factor for integral I_2, equal to $\frac{1}{4}(n-0.2)$
a factor, equal to $(U/U_0)_{\text{T.E.}}^{-0.25}$

$$I_1 = \int_0^{\text{T.P.}} \left(\frac{U}{U_0}\right)^5 d\left(\frac{s}{c}\right)$$

$$I_2 = \int_{\text{T.P.}}^{\text{T.E.}} \left(\frac{U}{U_0}\right)^4 d\left(\frac{s}{c}\right)$$

2. ANALYSIS

The problem of calculating the profile drag coefficient of any aerofoil consists essentially of estimating the momentum thickness of the boundary layer at the trailing edge.

To find the momentum thickness at the trailing edge the momentum thickness at the transition point is first evaluated.

It has been found that a modification of the equations due to Young[3] gives very close agreement to the usual Pohlhausen solution, and leads to

$$\left(\frac{\theta}{c}\right)_{\text{T.P.}} = \left\{\frac{0.664}{R^{\frac{1}{2}}\left(\frac{U}{U_0}\right)^3_{\text{T.P.}}}\right\} (I_1)^{\frac{1}{2}} \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where

$$I_1 = \int_0^{\text{T.P.}} \left(\frac{U}{U_0}\right)^5 d\,\frac{s}{c} \quad . \quad . \quad . \quad . \quad . \quad (2)$$

Reference 2 then suggests that the momentum thickness at the trailing edge is given to good approximation by

$$\left(\frac{\theta}{c}\right)_{\text{T.E.}} = \frac{1}{\left(\frac{U}{U_0}\right)^{H+2}_{\text{T.E.}}}\left[\frac{(1+n)k}{R^n}\int_{\text{T.P.}}^{\text{T.E.}} \left(\frac{U}{U_0}\right)^{(H+1)(n+1)+1} d\,\frac{s}{c} + \left(\frac{\theta}{c}\right)^{n+1}_{\text{T.P.}} \left(\frac{U}{U_0}\right)^{(H+2)(n+1)}_{\text{T.P.}}\right]^{\frac{1}{n+1}}$$

. . . . . (3)

TABLE I

CALCULATION OF PROFILE DRAG FOR N.A.C.A. 64,-012 AEROFOIL AT ZERO INCIDENCE

TALE IA

$\frac{x}{c}$	$\frac{U}{U_0}$	$\left(\frac{U}{U_0}\right)^4$	$\left(\frac{U}{U_0}\right)^5$	I_1	I_2
0	0	0	0	0	0
0.05	1.099	1.468	1.613	—	—
0.10	1.123	1.593	1.789	0.137	1.257
0.20	1.148	1.738	1.995	—	—
0.30	1.162	1.823	2.118	0.533	0.912
0.40	1.171	1.882	2.204	—	—
0.50	1.136	1.664	1.890	0.960	0.545
0.60	1.093	1.428	1.561	—	—
0.70	1.043	1.183	1.234	1.272	0.260
0.80	0.989	0.956	—	—	—
0.90	0.935	0.764	—	—	—
1.00	0.881	0.602	—	—	0

TABLE 1B For $R=10^7$, $a=1.032$ (from Fig. 3)

(1)	Transition point	0.1	0.3	0.5	0.7	
(2)	$(U/U_o)_{T.P.}$	1.123	1.162	1.136	1.043	
(3)	$(U/U_o)^3_{T.P.}$	1.416	1.569	1.466	1.135	
(4)	$(\theta/c)_{T.P.} \times 10^5$	5.49	9.77	14.04	20.87	$=0.664\times 10^5 (I_1/R)^{\frac{1}{2}}/(U/U_o)^3_{T.P.}$
(5)	R_{θ_1}	617	1135	1595	2180	$=R\,(\theta/c)_{T.P.}\,(U/U_o)_{T.P.}$
(6)	n	0.214	0.201	0.195	0.190	From Fig. 1
(7)	$b\,(1+p)$	0.000382	0.000419	0.000438	0.000452	From Fig. 2
(8)	$I_o b\,(1+p)$	0.000480	0.000382	0.000239	0.000117	$I_2\times(7)$
(9)	$3.5\,(n+1)$	4.25	4.20	4.18	4.165	
(10)	$(U/U_o)_{T.P.}^{3\cdot5(n+1)}$	1.636	1.878	1.705	1.191	
(11)	$(\theta/c)_{T.P.}^{n+1}\times 10^6$	6.71	15.22	24.89	41.71	
(12)	$(10)\times(11)$	0.000011	0.000029	0.000042	0.000050	
(13)	$(8)+(12)$	0.000491	0.000411	0.000281	0.000167	
(14)	$1/(n+1)$	0.824	0.833	0.837	0.840	$\frac{1}{(13)^{n+1}\times 4a}$
(15)	C_{D_o}	0.00774	0.00624	0.00440	0.00277	

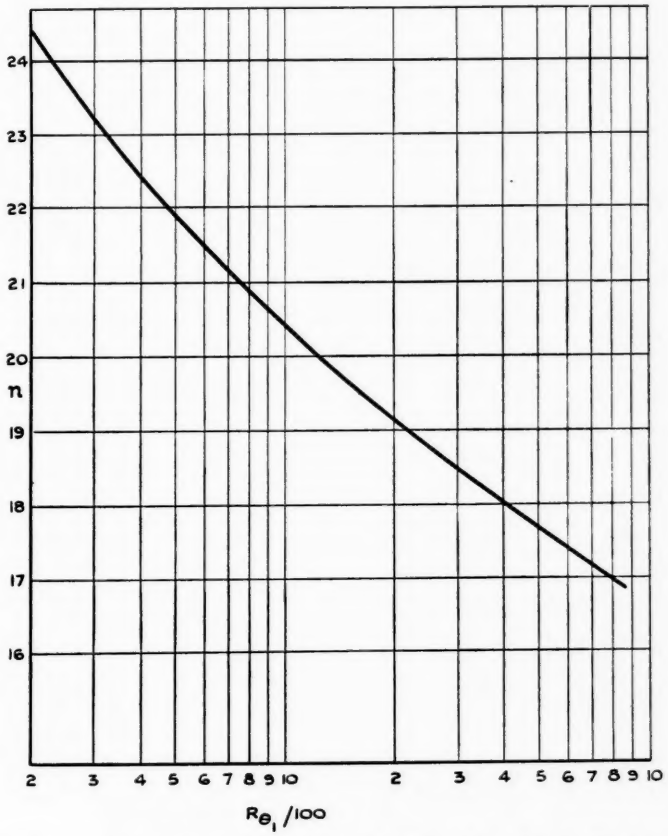

Fig. 1. Values of n for use in rapid estimation of aerofoil profile drag. (Calculated from the method of Ref. 2.)

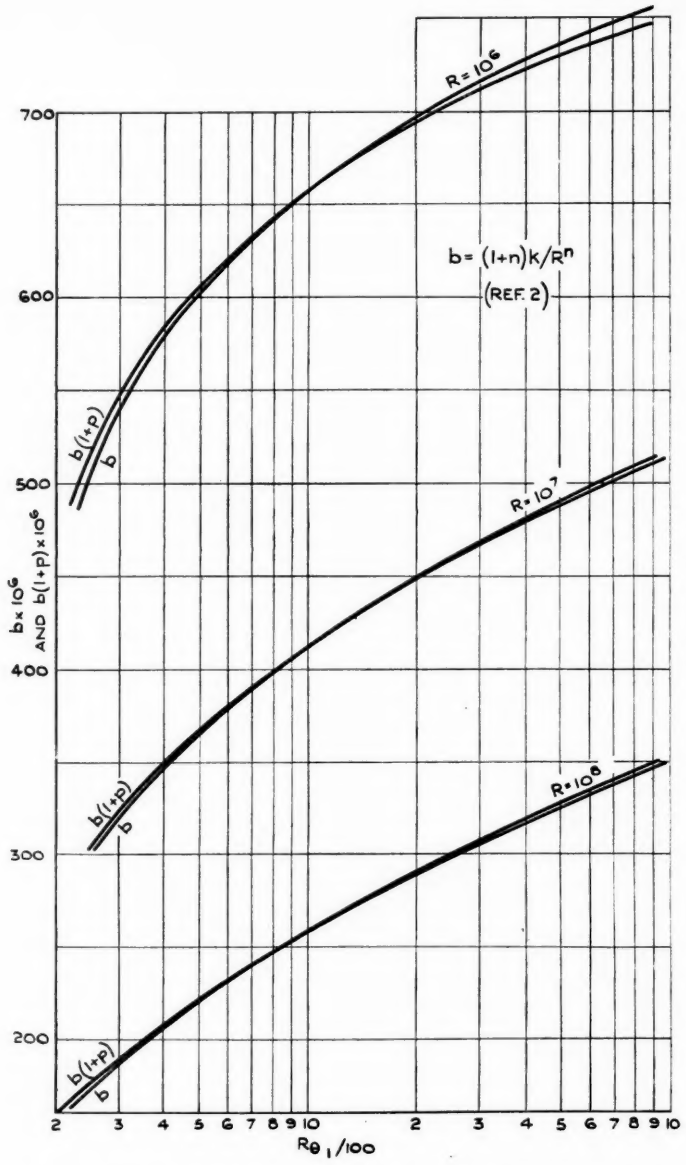

Fig. 2. Values of $b\ (1+p)$ and b for use in rapid estimation of aerofoil profile drag.

In practice, however, it is found that equation (3) may be replaced with no loss of accuracy by the expression

$$\left(\frac{\theta}{c}\right)_{\text{T.E.}} = \frac{1}{\left(\frac{U}{U_0}\right)^{3.5}_{\text{T.E.}}} \left[b\,(1+p) I_2 + \left(\frac{\theta}{c}\right)^{n+1}_{\text{T.P.}} \left(\frac{U}{U_0}\right)^{3.5\,(n+1)}_{\text{T.P.}} \right]^{\frac{1}{n+1}} \quad . \quad . \quad (4)$$

where $b = \dfrac{(1+n)\,k}{R^n}$, a function of R_{θ_1} and R,

$p = \frac{1}{4}(n - 0.2)$, a function of R_{θ_1}, and is a correction factor,

$$I_2 = \int_{\text{T.P.}}^{\text{T.E.}} \left(\frac{U}{U_0}\right)^4 d\,\frac{s}{c}$$

and H has been given the numerical value 1.5.

The profile drag coefficient of one surface of the aerofoil may then be obtained from the equation[1]

$$C_{D_0} = 2\left(\frac{\theta}{c}\right)_{\text{T.E.}} \left(\frac{U}{U_0}\right)^{\frac{1}{2}(H+5)}_{\text{T.E.}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

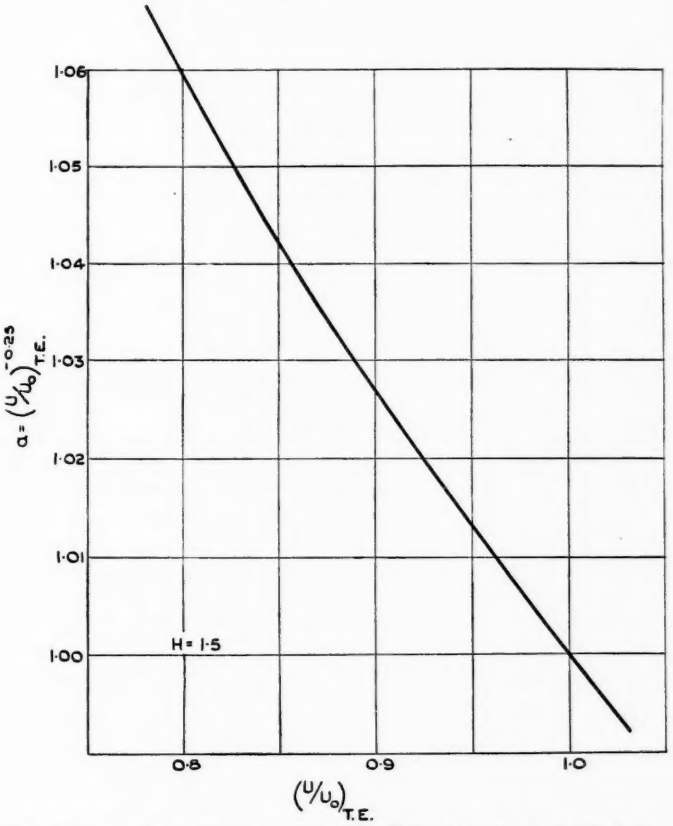

Fig. 3. Values of a for use in rapid estimation of aerofoil profile drag.

Combining equations (1), (2), (4) and (5) it is found that for a symmetrical aerofoil at zero incidence

$$C_{D_0} = 4a\left[b(1+p)I_2 + \left(\frac{\theta}{c}\right)^{n+1}_{T.P.}\left(\frac{U}{U_0}\right)^{3.5\,(n+1)}_{T.P.}\right]^{\frac{1}{n+1}} \quad . \quad . \quad (6)$$

where

$$a = \left(\frac{U}{U_0}\right)^{-0.25}_{T.E.} .$$

The quantities $b(1+p)$, b, n and a are most conveniently given in graphical form (Figs. 1, 2, 3) and the integrals I_1 and I_2 may be evaluated rapidly for any given pressure distribution.

A specimen calculation is set out in Table I. Here the integrals I_1 and I_2 are evaluated with respect to x/c rather than s/c. It was found that this simplification resulted in an error in the calculated values of less than one per cent. in the case of a 20 per cent. thick aerofoil (Table II).

For other Reynolds numbers the second part only of Table I need be repeated. For one symmetrical aerofoil, four selected transition point positions and three Reynolds numbers, the complete calculation can be accomplished in approximately one hour.

Table II gives a comparison between values of profile drag calculated by this and other methods. The differences are never more than two to four per cent.

TABLE II

COMPARISON OF RESULTS OBTAINED BY VARIOUS METHODS

$R = 10^7$

Aerofoil	*Method of calculation*	*Transition point*	C_D (*top*)	C_D (*bottom*)	C_{D_0}
N.A.C.A. 65, 1—012	R. C. Lock[5]	0.3	—	—	0.00654
		0.7			0.00286 (interpolated)
	Equation (6)	0.3	—	—	0.00652
		0.7			0.00290
20 per cent thick wing of Ref. 4	Winterbottom and Squire[4]	0.4	0.00816	0.00576	0.00696
		0.6	0.00554	0.00404	0.00479
	Method of Section 3 using velocity distribution along surface	0.4	0.00846	0.00585	0.00715
		0.6	0.00573	0.00406	0.00490
	Method of Section 3 using chordwise velocity distribution	0.4	0.00839	0.00584	0.00711
		0.6	0.00564	0.00406	0.00485
Flat plate	Royal Aeronautical Society Data Sheets	0.1			0.0056
		0.3			0.0047
		0.5			0.0038
		0.7			0.0027
	Method of Section 3 (Fig. 4)	0.1			0.0057
		0.3			0.0048
		0.5			0.0038
		0.7			0.0026

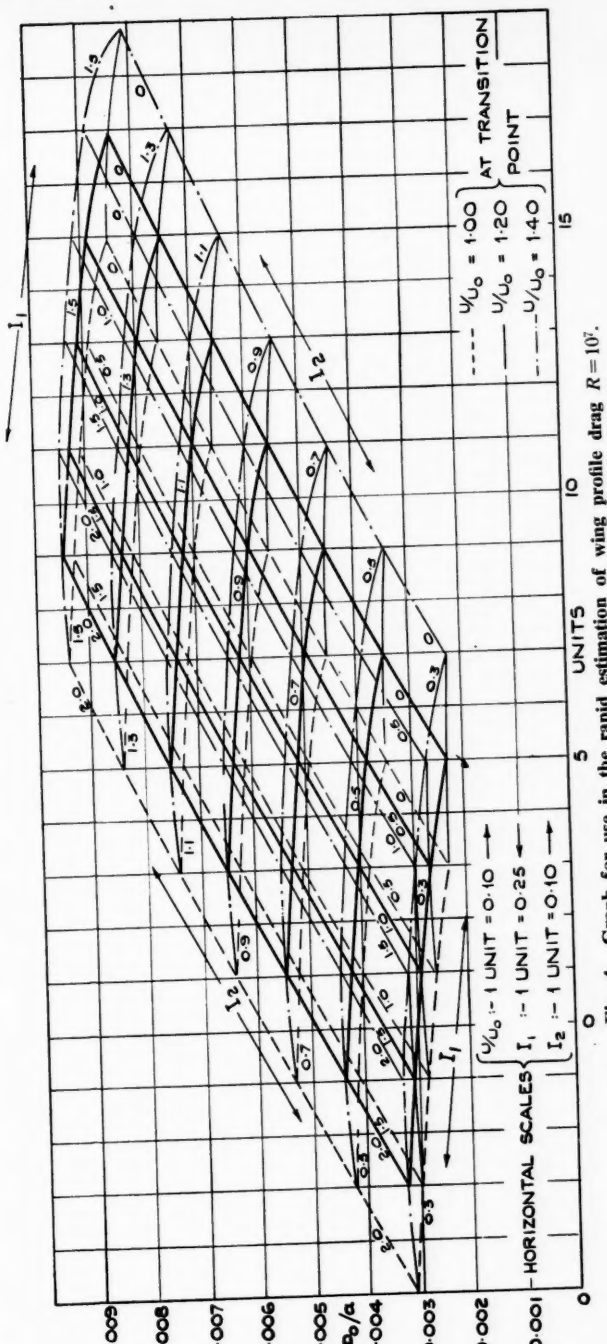

Fig. 4. Graph for use in the rapid estimation of wing profile drag $R = 10^7$.

3. A FURTHER SIMPLIFICATION

Where profile drag coefficients are being constantly evaluated it is possible to reduce the computation even further.

Equations (1), (2) and (6) may be written in the form $C_{D0} = a \times F[I_1, I_2, (U/U_0)_{T.P.}, R]$.

Values of the function F may be calculated for a range of values of the parameters.

Figure 4 shows a plot in the form of a lattice of C_{D0}/a against I_1, I_2 and $(U/U_0)_{T.P.}$ for $R = 10^7$.

Use of a set of such lattices together with equation (7) and Fig. 3 (to give the value of a) enables C_{D0} for a given aerofoil to be obtained as soon as the integrals I_1 and I_2 have been evaluated.

As Table II indicates, Fig. 4 appears to give values of C_{D0} some two to four per cent. too high.

4. CONCLUSION

The calculation of aerofoil profile drag may be considerably shortened with no significant loss in accuracy. The profile drag coefficient may be expressed as a function of two integrals of the velocity distribution.

ACKNOWLEDGMENT

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*The Technique of Resonance Testing and Flutter Calculations as applied to Fighter Aircraft Design**

by

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SUMMARY

The purpose of this paper is to explain in simple terms the methods employed in, and the principles underlying, the technique of resonance testing and flutter calculations and to place that technique in its proper perspective within the framework of fighter aircraft design. No attempt is made to present original work, or to examine the more advanced aspects of the subject as both of these are considered to be outside the scope of the paper.

The reasons behind the growth in importance of resonance tests and flutter calculations are dealt with first. The technique of ground resonance tests is then given in detail. A few words follow on model resonance tests, the calculation of normal modes, and some aspects of flight resonance tests. The technique of flutter calculations is considered last of all, an attempt being made to give a simple explanation of "flexure-torsion" flutter, plus the basic theory of two-freedom flutter leading to the Lagrangian equations. The methods and instruments described in the paper may be regarded as typical, but as the subject is continually evolving they are far from final.

Some present trends in technique are mentioned, together with the difficulties experienced in dealing with the aerodynamic forces in the transonic region. It is essential that these forces be assessed, and the only known method is by experiment.

1. INTRODUCTION

The power of the turbo-jet engine has increased the speed of present-day fighters right up to the so-called sonic barrier. Performances at Mach numbers close to unity have entailed the adoption of swept-back wings in order to delay the shock stall and raise the critical Mach number as much as possible. These conditions have presented in their most acute form the problems associated with control reversal, stability and flutter. Since it has become increasingly necessary to allow for the effect of the elastic deformations of the aircraft structure in stability calculations, the boundary between them and flutter calculations has become quite nebulous. In fact stability and flutter represent the two ends of the same story; stability being concerned primarily with low frequency oscillations, with body movements predominant, while flutter consists of a relatively high frequency oscillation with elastic deformations of the structure predominant. This paper will be confined to the flutter problem.

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Up to a few years ago aircraft designers could calculate the torsional and flexural stiffness of the wings, fuselage, empennage and control surfaces of an aircraft; ensure that certain conveniently simple criteria were satisfied, and later check their calculations by simple full-scale static stiffness tests, in order to be reasonably certain of having a flutter-free aircraft. In fact, the adoption of these semi-theoretical, semi-statistical criteria initiated by Roxbee Cox and later elaborated by Collar and Broadbent, plus the mass-balancing of all control surfaces, has done yeoman service in the fight against flutter. Today the rigid application of these stiffness criteria tends to produce inordinately heavy structures and, apart from this, it is difficult satisfactorily to adapt to swept surfaces criteria evolved for straight ones. An attempt has been made to produce a rough but simple formula for the flutter speed of a swept-back wing, but like the Küssner relationship that preceded it for straight wings, it requires a knowledge of the lowest "dangerous" resonant frequency of the wing.

The upshot of this situation is that the designer has been forced, with some reluctance, to resort to the heavier weapons of resonance tests, flutter calculations and the calculation of normal vibrational modes; these last as a precursor to the resonance tests. The heavier the weapon, the heavier the recoil; in this case the recoil takes the form of the cost in money and man-hours necessary to obtain the required information. An *ab initio* routine flutter calculation may take two mathematicians, plus two computers with automatic calculating machines, up to two months to perform. The calculation of normal vibrational modes for one component, such as a wing, may be almost as arduous. A full-scale ground resonance test may immobilise a prototype aircraft representing a capital outlay of some £250,000 for about a fortnight at a most critical stage in its career, and require the labours of six technicians for a month or more from the start of testing to the publication of the final report. Such are the penalties of progress, and they are unavoidable.

The importance of the results obtained from ground resonance tests on the complete aircraft can hardly be exaggerated, as will be seen later, either for the direct information to be drawn from them, or as an adjunct to flutter calculations. These results must provide the final judgment on the basic flutter picture, and depending upon what is found, elaborate calculations or tests may have to be undertaken. It is hardly surprising, therefore, that the performance of ground resonance tests on prototype aircraft is an Airworthiness Requirement, and these tests will be dealt with in detail.

Notation and Abbreviations

Dots over symbols denote differentiation with respect to time. Suffixes "1" and "2" refer to the number of the mode considered.

q_1, q_2	displacements at reference section
$a, b \ldots$	functions of position (*see* equation (1))
m	element of mass at a point on the wing
T	total kinetic energy of wing
A_{11}, A_{12}, A_{22}	Σma^2, Σmab, Σmb^2, respectively
t	time
F, F_1, F_2	forces (*see* equations (6) and (6*a*))
E_{11}, E_{22}, E_{12}	dynamic stiffness coefficients (*see* equations (6) and (6*a*))
U	potential energy
z	leading edge displacement
α	wing incidence
e, h, j, k	functions of position in equations (11) and (12)
δ	denotes the value for an elementary wing strip (*see* equation (13))
W	aerodynamic work
L	lift
M	pitching moment
D_1, D_2, D_3, D_4	differential operators (*see* equations (14) to (17*a*))
λ, μ, η	constants in equations (15) and (16)

Q_1, Q_2	generalised aerodynamic forces
n	number of freedoms
r, s	particular freedoms ($=1, 2, 3, \ldots, n$) (in Section 6.4)
q_0, q_{r0}, q_{s0}	amplitudes
ω	circular frequency
ω_1	resonance circular frequency
f	flutter frequency
c	chord length
V	speed of flight
ν	frequency parameter
ρ	air density
X	$E_{11}/(\rho V^2 c^3)$
Y	$E_{22}/(\rho V^2 c^3)$
g	acceleration due to gravity
$f(y)$	displacement function (*see* equation (28))
y	spanwise co-ordinate
s	spanwise co-ordinate of reference station (Section 6.5)
$F(y)$	torsional displacement function (*see* equation (30))
m	number of test points (Section 6.5)
$y_1, y_2, \ldots s$	position of test points along span (Section 6.5)
K_r	ratio of amplitude at y_r to amplitude at s (Section 6.5)
$p_1, p_2 \ldots . p_m$	coefficients in equation (31)
M	Mach number (Section 7)
ε	angle of downwash
S.H.M.	simple harmonic motion
T.P.	tailplane
c.p.s.	cycles/sec.
A.C., D.C.	alternating and direct current, respectively
h.p.	horsepower
E.M.F.	electromotive force
L.E.	leading edge

2. THE TECHNIQUE OF GROUND RESONANCE TESTS

2.1. INTRODUCTION

The object of resonance tests is to obtain as complete a record as possible of the vibrational behaviour of the aircraft structure over the critical frequency range applicable to flutter.

The work falls conveniently into three parts, thus:—

2.1.1. The determination of those frequencies of vibration at which the amplitudes of motion of the major components of the structure and of the control surfaces reach peak values. These frequencies are known as the "resonant frequencies" and correspond to the fundamental or overtone frequencies of the various parts of the structure and controls.

2,1,2, The determination of the manner in which all parts of the aircraft vibrate at each of the resonant frequencies, as defined by the amplitudes of the motion from the equilibrium position. Such a manner of vibration for any given frequency is known as the "normal elastic mode," or simply as the "normal mode" or "mode" for that frequency. Those points in the structure remaining at rest, while the remainder of the structure vibrates, are known as "nodal points" and the locus of such points define the "nodal lines" for the given "mode."

2.1.3. The interpretation of the results in the light of experience in order to assess the susceptibility of the aircraft to flutter. Even today this is more of an art than a science.

Since the tests are usually performed in still air, as against *in vacuo*, and the aircraft is not a perfectly elastic structure, an exciting force has to be applied

continuously during the tests in order to overcome the aerodynamic and structural damping ("solid friction," slip at joints, for example) and thus maintain the motion. This force is made to vary sinusoidally with time, and to be capable of a continuous variation in frequency between practical limits. It must be applied at a point on the structure which is unlikely ever to be a nodal point during the investigation, since any mode with a nodal line passing through the chosen point of excitation could not be induced, and thus would be omitted. Extremities of the structure are suitable points of application, and for structural strength reasons the fuselage nose is often a convenient position.

The exciting force is applied vertically and laterally in turn, and also occasionally in a fore-and-aft direction.

The vertical excitation (Fig. 1) induces symmetrical vertical oscillations of the wings, tailplane, ailerons and elevators, plus fuselage vertical flexure. Fore-and-aft excitation would produce symmetrical oscillations in the chordwise plane of the wing and tailplane

The lateral excitation (Fig. 2) induces anti-symmetrical vertical and fore-and-aft oscillations of wings and tailplane, lateral flexure and torsion of the fuselage, and lateral oscillations of the fin and rudder.

It will be appreciated that the motions induced can be quite complex overtones, comprising both flexure and torsion of the wings, for example, and not just the simple fundamental modes shown in the figures.

2.2. Test apparatus

One of several types of mechanical or electrical exciter available to produce the vibrating force consists of two identical wheels lying in a common plane, and in geared contact at their rims (Fig. 3). Both wheels carry adjustable out-of-balance weights, the combined centrifugal force of which, when the wheels are rotating, cancels out in all directions except along a line at right angles to the common centre-line of the wheels. Power is supplied to one wheel from a variable speed A.C. or D.C. motor, the other wheel being driven through the geared rim. For small to medium-sized aircraft a 3 h.p. motor is adequate, but power in hand is essential, otherwise hunting takes place at the resonant frequencies owing to the increased energy absorption. A good flywheel is helpful in this respect. The static out-of-balance of an exciter suitable for such a motor would be arranged to vary in fixed increments from 0 to $2\frac{1}{2}$ lb. in. The insertion of a gearbox between motor and exciter permits a maximum working frequency range from 5 to 65 c.p.s., which is

Fig. 1. Vertical excitation.

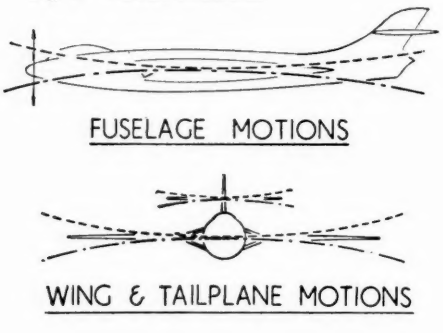
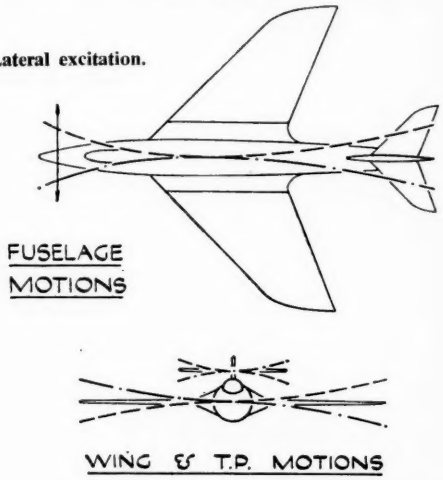


Fig. 2. Lateral excitation.



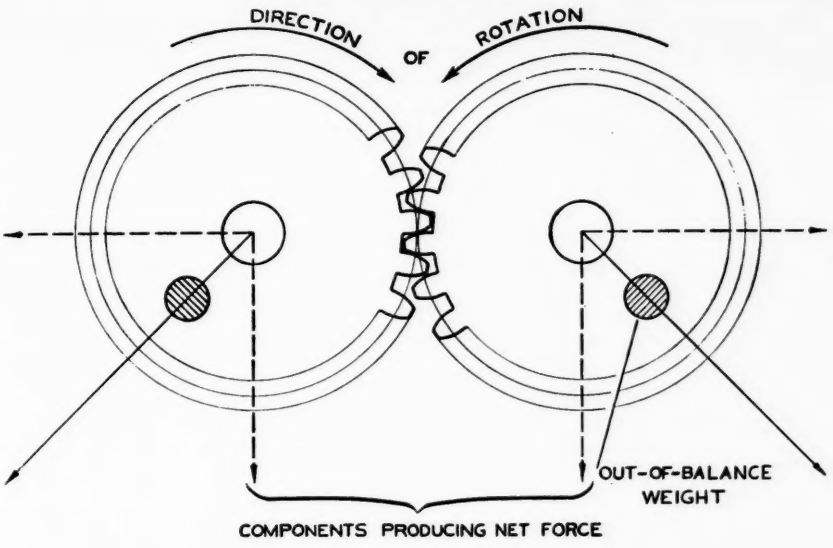


Fig. 3. Linear exciter.

normally sufficient to cover all significant frequencies likely to be found on fighter aircraft. In fact, normal modes with resonant frequencies greater than 30 c.p.s. are unlikely to be components of a flutter motion; this point is amplified later.

The vibrations induced in the aircraft by the apparatus described are measured by electrical pick-ups.

These can be of three fundamental types, measuring either acceleration, velocity, or amplitude.

The velocity-measuring type is in general use, and it will suffice to describe this type of pick-up, which exists in two forms (Fig. 4). In each of these, a coil is suspended by a spring of low natural frequency within a permanent magnet forming the outer casing of the instrument, relative movement of the coil and case producing an E.M.F. proportional to the velocity of movement. In the "seismic" form of pick-up the case of the instrument is held against the aircraft structure and vibrates with it, the coil remaining relatively immobile because of its own inertia; in the "non-seismic" form of pick-up the interior coil is directly vibrated by contact with the aircraft through a light rod, the outer casing being held motionless. These pick-ups may be reliably calibrated for amplitude against frequency, and give the correct phase indication for the signal.

The seismic pick-up, which is easier to manipulate than the non-seismic, is used for all parts of the rigid structure. The relatively large weight of the case, however, imposes excessive damping on the virtually free flying control surfaces, and makes necessary the use of the non-seismic pick-up (with its light-weight moving coil) at such stations. This pick-up requires a stand to hold the case still relative to the equilibrium position of the vibrating structure, in order to keep the trace steady on the screen of the recording oscilloscope. Even on the main structure, the operator using a seismic pick-up should use the minimum pressure consistent with no "bumping," otherwise the amplitudes throughout the aircraft will be radically altered.

Figure 5 shows the assembly of resonance test equipment. The aircraft is shown with the exciter mounted in the nose, driven through the gearbox by a motor (D.C. in this case). Coupled to the motor is the tachometer with its leads to the revolution counter. Power for the motor is taken from the A.C. mains to the starter and speed control unit through an A.C./D.C. rectifier. That completes the apparatus for

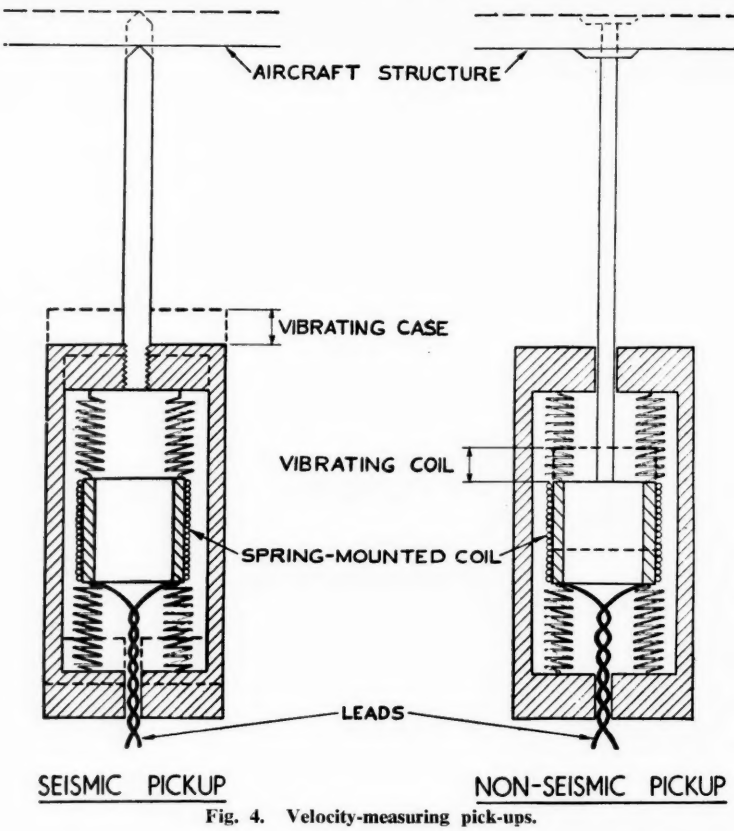


Fig. 4. Velocity-measuring pick-ups.

applying the exciting force and measuring its frequency. The vibration measuring equipment is shown grouped on the right hand side of the figure.

The movable measuring pick-up may be applied to any desired point on the aircraft; as mentioned earlier the signal from the pick-up is a function of the velocity of the vibration. This signal is fed to the integrating box which contains an integrating and a calibrating circuit. The integrating circuit consists of a relatively simple arrangement of resistances in series and in parallel with a fixed condenser. The signal is there integrated once with respect to time in order to produce amplitude. It is then recorded after amplification on a single beam cathode ray oscilloscope which indicates the signal as a vertical straight line trace (the time base being absent). The length of the trace is proportional to the amplitude of vibration of the aircraft structure. As only the relative, and not the absolute amplitude of different parts of the aircraft is required, the trace is calibrated to give a non-dimensional quantity obtained by multiplying the amplitudes in inches by the all-up weight of the aircraft in lb. and dividing the product by the applied out-of-balance of the exciter in lb. in.

This apparatus enables relative amplitude of vibration of any part of the aircraft structure to be measured. It is still necessary, however, to determine the phase relationship of these amplitudes, and to do this the pick-up signal from any desired station on the structure is compared with that of a fixed master pick-up which, in order to avoid a node if possible, is usually situated on one wing tip. This master pick-up has its own integrating/calibrating circuit and single beam cathode ray

oscilloscope. (This is for use during the recording of a mode, as will be seen later). The signals from the two pick-ups are then taken from their single beam oscilloscopes and fed simultaneously into a double beam cathode ray oscilloscope with a time base. This shows the two signals as two separate sinusoidal traces whose phase angle may be roughly measured by inspection. The phase angle of any point compared with the wing tip then gives its phase relative to any other similarly compared point. Naturally the phase angle depends on the direction in which the pick-up is pointing, and care must be taken not to forget this during tests.

2.3. Test Procedure

The aircraft is fully loaded as for flight, ballast being added in lieu of the pilot, and the fuel tanks are filled to a level appropriate to a mean flight condition, say half to two thirds full. On a fighter it is usually sufficient to investigate a single condition of loading. The mounting of the aircraft is important, and its natural frequency on its supports should be not more than a third of the fundamental wing frequency, say 3 to 4 c.p.s. With a nose-wheel undercarriage this can usually be achieved by standing the aircraft on its undercarriage in the normal way and reducing the tyre pressure to some 60 per cent. of the correct value. With a tail-wheel undercarriage the rear fuselage would have to be suspended from an elastic sling. The cockpit flying controls are lightly lashed by elastic cord in order to maintain the surfaces in neutral position without unduly damping their response to induced vibration. With the exciter mounted in the nose, and the master pick-up fixed to the wing tip, the aircraft is ready for testing.

The first step is to determine the "resonant frequencies" for the aircraft structure and control surfaces under both vertical and lateral excitation. This is done by applying the measuring pick-up in turn to a series of master stations at the

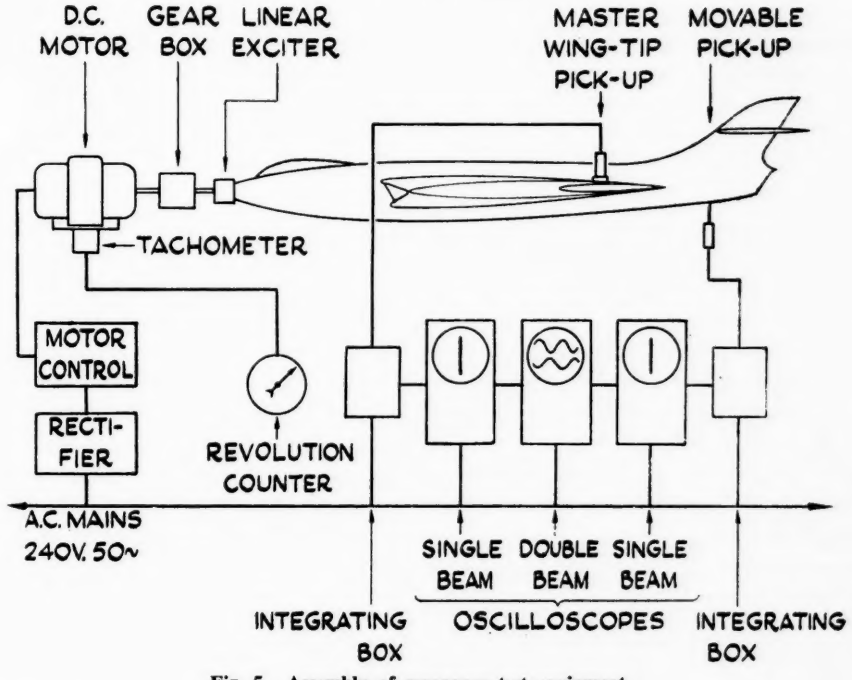


Fig. 5. Assembly of resonance test equipment.

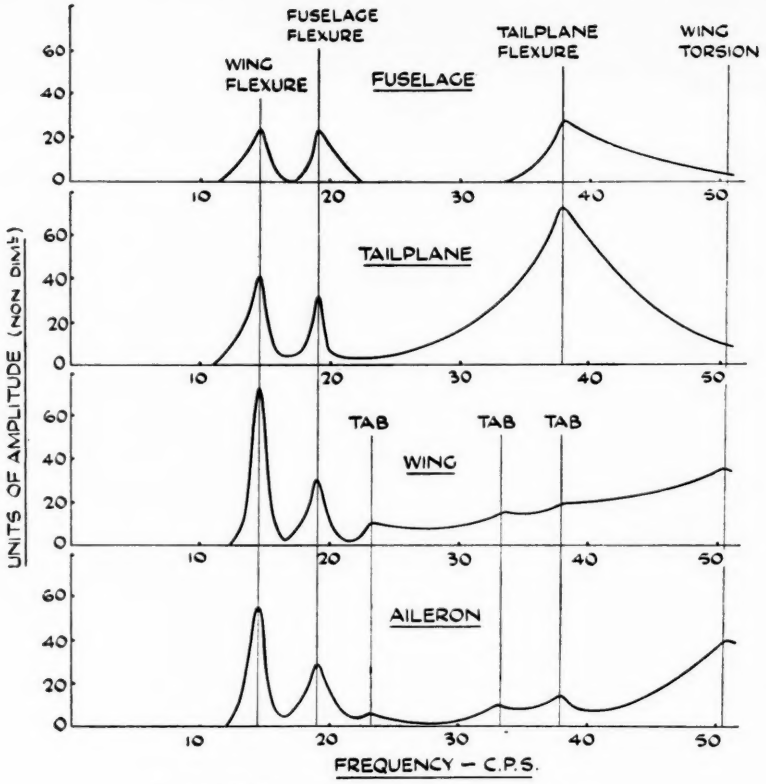


Fig. 6. Typical panoramas for vertical excitation.

wing, tailplane and fin tips, fuselage tail end, and the trailing edge of all control surfaces and tabs, while the frequency is varied in increments of one c.p.s. throughout the range to be investigated, say from 5 to 50 c.p.s., and the amplitudes recorded. (Extremities are chosen for master stations as they are unlikely ever to be nodal points.) The amplitude/frequency curves for each of the master stations are plotted and are known as "panoramas." The peaks and their frequencies are then re-determined with greater accuracy.

Typical panoramas for a selection of master stations are shown in Fig. 6. The peaks on these curves correspond to the resonant frequencies of the structure and are the result of increased response to the excitation as the frequency approaches and coincides with the natural frequency of a component of the aircraft structure. It will be appreciated that there is bound to be inter-action to a greater or lesser degree between the various parts of the structure. For example, flexure of a swept-back wing will induce body motions and *vice versa*. This in the explanation of the frequency "bands" which run through the panoramas, peaks appearing on, say both fuselage, wing, aileron and aileron tab at a common frequency. The panoramas are then analysed in order to classify the resonant frequencies and to determine, as far as possible, the particular modes or types of vibration to which they correspond, such as wing fundamental flexure, rear fuselage torsion, fin flexure, and so on. This process is a matter of experience plus observation during the recording of the

panoramas. It may be necessary to examine further the motion of a few parts of the structure before the precise nature of a resonant frequency is obtained.

The second step is to determine the normal mode of vibration for each of the major structural resonances. This is done by recording the amplitude of vibration and phase relationship for a given resonant frequency at enough points over the whole aircraft to enable the motion of its structure and controls to be recorded graphically. To obtain consistent results one operator should take all the readings with the measuring pick-up, and as quickly as possible compatible with accuracy. The motor speed must be strictly controlled in order to keep exactly on resonance, and this is the second function of the master pick-up (the first being phasing). It is by keeping the vertical trace from the master pick-up constant in length that constant frequency is best obtained.

As may be seen from Fig. 7, the results are usually presented as curves of amplitude for the various structural units in comparison with scale drawings of the aircraft, so that the amplitude of any point may conveniently be read off. It is usual to plot the amplitudes along the leading edge and rear spar of the wings and tailplane, and similarly for the fin, in order that the twist of the aerodynamic surfaces may be computed, as well as their deflections. Hitherto the assumption has been made that all points will be exactly in or out of phase with each other, as in a truly elastic body, so that by plotting the amplitudes as positive or negative quantities to correspond with coincident or opposing phases, the relative movements of the various parts of the structure may be compared. Apart from the smaller amplitudes the foregoing is approximately true, but structural damping does cause phase displacement throughout the structure, and in future it may be necessary to take account of the actual phase angles in order to obtain a truer picture of the mode. In addition to the amplitudes the nodal lines are also shown. These may be obtained by interpolation from the amplitude curves or by directly traversing the pick-up over the aircraft itself and determining the actual lines of zero amplitude.

It should be noted that with control surface resonances (Fig. 8) the investigation of the mode is usually confined to plotting the amplitude across two chordwise sections traversing the control surface, and at one check section on the other side of the aircraft.

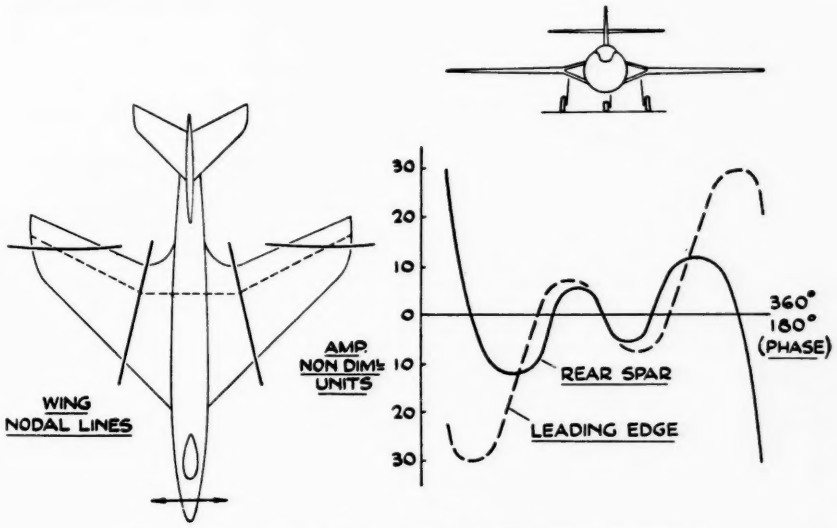


Fig. 7. Typical partial mode. Wing motions, lateral excitation.

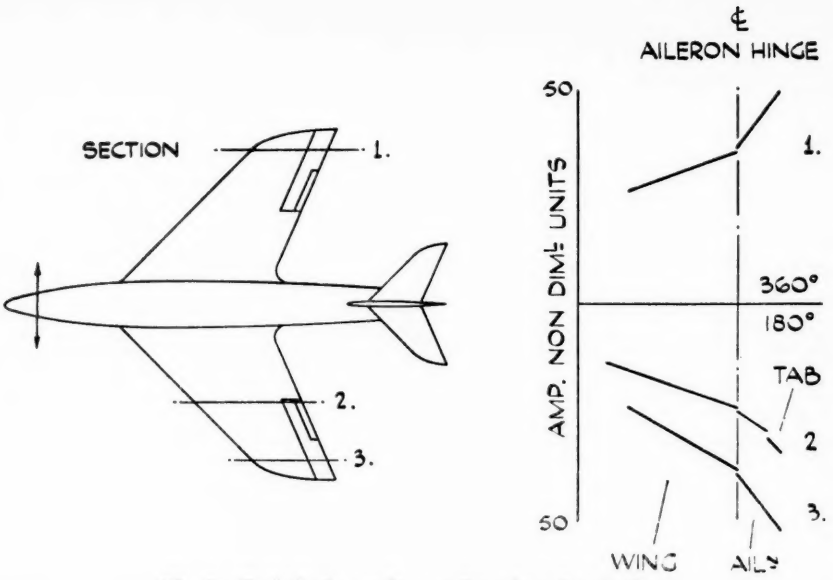


Fig. 8. Typical wing surface motions, lateral excitation.

This completes the experimental investigations performed during a routine test, but further work may have to be done, such as direct excitation of the control surfaces to obtain circuit resonance, and stick phasing in order to distinguish circuit resonance from bodily movement. If engine vibrations have to be considered a whole new field of investigation is opened up, and the frequency range will have to be extended to 700 or 1,000 c.p.s.

2.4. Interpretation of the Test Results

The third, and most difficult, step is the interpretation of the results. Since, in practice, flutter troubles usually involve the control surfaces, the results are examined to see whether or not these are behaving well. If the mass-balancing is adequate the control should follow the main surface motion without excessive angular movement, or the movement should be such as to dampen the motion. Further, there should not be too much relative twist between the inboard and outboard ends of the control surface. The nodal lines are examined to see if they are ever in the proximity of a mass-balance weight. Naturally a mass-balance weight with a nodal line through it is ineffective in that particular mode. It is one big advantage with distributed mass-balance weights that, apart from reducing the necessity for such a torsionally stiff control surface, it is unlikely that the nodal line will lie along the whole of the balance weight, and hence some balance is available in all cases. With a remote mass-balance weight a node must never lie between the weight and the control surface, otherwise the result is a dangerous anti-balance effect.

A further possible cause of flutter (about which little is known) may be the proximity of any two of the natural frequencies of the main and auxiliary controls and the aircraft structure, and this may lead to flutter even on a fully mass-balanced system.

Spring tabs are in a class apart, and would need a paper to themselves. The natural frequency of the spring tab on its spring with control surface fixed should be at least 1.5 times that of the main surface fundamental frequency and also at least

twice the natural frequency of the control surface about its hinge line with tab fixed. With the radical design changes now taking place the possibility of main structure flutter cannot be eliminated. Those modes producing incidence changes in the outer portions of the aerodynamic surfaces are the important factors here. To avoid flexure-torsion flutter, for example, the resonant flexural and torsional frequencies should be well separated, and the torsional frequency should be high, that is greater than 30 c.p.s. Examination of the modes will soon reveal configurations and combinations susceptible to flutter, such as the parabolic nodal line on a swept-back wing, but this evidence is not necessarily conclusive, and flutter, if it occurred at all, might do so at a speed beyond the aircraft's performance.

Hence, although small modifications to mass balances, control surfaces and possibly the empennage (such as re-skinning a tailplane) might be done as the result of resonance tests alone, no major re-design would be done unless something obviously catastrophic was indicated. Normally, the sequel to resonance tests is a flutter calculation plus simultaneous careful flight testing.

3. MODEL RESONANCE TESTS *VERSUS* CALCULATION OF NORMAL MODES

It may be argued that the ground resonance test comes too late in the design of the prototype, and that the information could be obtained sooner from models. A truly accurate scale model would provide the necessary information, but would be almost as long in building as the real aircraft, and the accuracy required would be beyond the practical workshop limits. Even a model confined to basic structure without controls would be a "*magnum opus*." Since the major structural resonances only would be obtained from such a model, a further simplification could be made, reducing the aircraft to a dynamically similar arrangement of elastically connected masses. This type of model is practical to make, but has to rely on calculated structural stiffnesses. That is the snag, and therefore the author believes that it would be better to abandon the tests and perform normal mode calculations on the dynamically equivalent elastic-inertia system. For example, with a wing idealised into four chordwise rods per semi-span and one equivalent rod for the fuselage, and allowing a translational freedom and a freedom in pitch for each of the five rods, the resulting ten second-order differential equations will produce the first eight resonances from the fundamental in a symmetrical vibration. Of these, the first five will be sufficiently accurate for use. Such a calculation will provide frequencies, modes and nodal lines in a time comparable to that required to perform a model test, let alone prepare the model. Hence, in the design stage, calculate; as a final check, test the real aircraft.

4. FLIGHT RESONANCE TESTS

A refinement on ground resonance tests would be resonance tests in flight. These would provide a record of what *really* happens to the aeroplane. The technical difficulties of obtaining suitable airborne apparatus and pick-ups, however, added to the considerable dangers involved, have delayed the development of this particular technique. Before the 1939-45 War the Germans tried it out on a four-engined Junkers aircraft; no one lived to tell the tale!

5. THE VIBROGRAPH RECORDER

There is a less exciting approach than actually inducing flutter in flight. This is by careful flight tests in conjunction with one or two vibrograph recorders. These are best described by looking at Fig. 9.

Externally, each instrument is a 4 in. cube in shape, and may be clamped to any convenient point of the aircraft structure. It can be positioned to record the amplitude and frequency of a vibration along any one of the three co-ordinate axes, vertical, lateral, fore-and-aft. A beam of light is projected through a slit in a screen

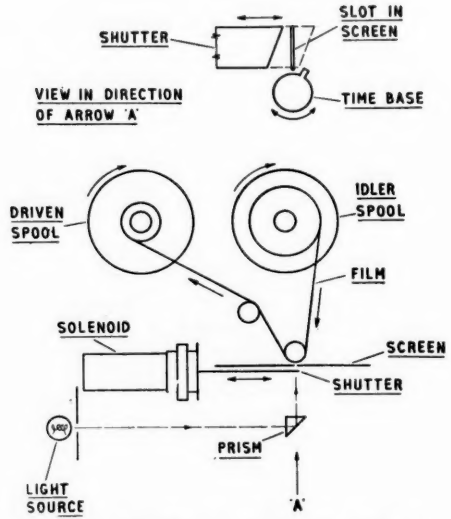


Fig. 9. Diagram of vibrograph recorder.

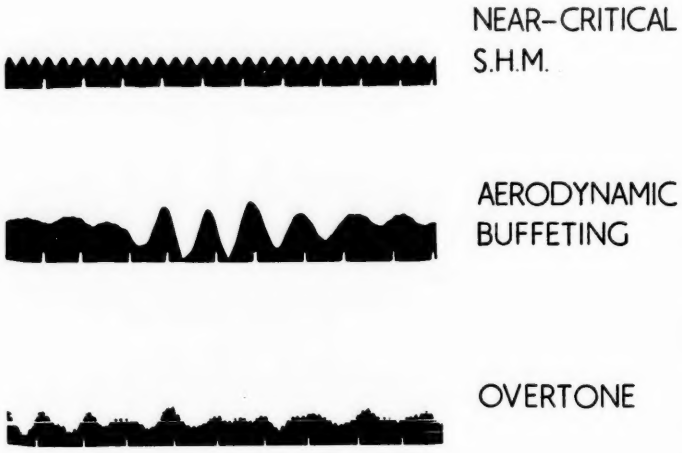


Fig. 10. Typical vibrograph traces

on to a moving 16 mm. film. The light is partly obscured by a guillotine shutter fixed to an aluminium ring on a light adjustable spring suspension, with eddy current damping. The adjustment is required as the instrument is affected by acceleration. When measuring vertical amplitudes, for example, the zero has to be set to the centre of the film under 1.0*g*. The instrument vibrates with its mounting on the aircraft, while the aluminium ring and shutter remain relatively immobile through their inertia, and hence more or less of the slot is open to the light. The result is a trace of the vibration against time. A time wheel makes a mark every 1/10 sec. and the magnification factor of such an instrument is about eight.

By fitting two of these instruments in, for example, the tail of an aircraft (one for vertical and one for lateral vibrations) and performing a series of "levels" during which the stick is jerked and the rudder bar kicked as the speed is increased in approximately 25 knot increments, a complete vibration history of the aircraft may be obtained. Typical traces are shown in Fig. 10.

If the condition is stable, the oscillation from the jerk on the controls will be damped out fairly quickly; if it is nearly critical it may be maintained an inordinately long time and the pilot will have to throttle back or climb to reduce speed and stop it. A vibration of the flutter type gives an even sinusoidal trace, while transient aerodynamic buffeting causes a ragged curve. Propeller and piston-engined aircraft usually exhibit complicated traces full of overtones. Airworthiness Requirements have been formulated defining the acceptable values of amplitude in both vertical, lateral and fore-and-aft directions for all frequencies up to 500 c.p.s.. The aircraft is split into three regions—extremities, power-plant, and central, extremities being allowed twice the central amplitudes. The cockpit region is covered by a curve defining the threshold of unpleasant vibration, and it would appear from this that the pilot is three times as sensitive as his wing tips! The vibrograph technique is extremely valuable, since, if trouble occurs, the amplitude, direction and frequency are found, enabling a better choice of modes to be made from the resonance tests for use in the subsequent flutter calculations.

6. THE TECHNIQUE OF FLUTTER CALCULATIONS

6.1. INTRODUCTION

Flutter occurs in various forms. Two examples are the compressibility flutter of control surfaces and the stalling flutter of propeller blades. By far the most common form of flutter is known as "classical" or "coupled" flutter, and unless otherwise qualified, the term "flutter" is assumed to refer to this.

Compressibility flutter occurs when oscillatory fore-and-aft movements of the shock-wave front on either side of the control surface are not in phase with one another. This induces control surface movements which in turn aggravate the oscillation, thus completing the cycle.

Stalling flutter occurs at high subsonic Mach numbers because at high angles of incidence near the stall, the value of the lift coefficient corresponding to a given incidence is greater when the angle is increasing than when it is decreasing. Thus a loop is formed on the end of the graph of lift coefficient against incidence, this loop being proportional in area to the net amount of work abstracted from the air stream to sustain or increase the oscillation.

The two examples just described have one thing in common; each has a single degree of freedom. This is control surface rotation in one case and blade twist in the other. For this reason each is fundamentally different in form from "classical" or "coupled" flutter.

Coupled flutter is the growing oscillation produced by a combination of two or more individually stable motions or degrees of freedom. Each of these motions alone would give a damped oscillation, such as the normal modes in a resonance test. Couple them aerodynamically and combine them in a suitable amplitude and

phase relationship, and flutter can result if the speed is high enough to make the coupling effective. Motions are said to be coupled when any one tends to induce the remainder, and the oscillations may be coupled aerodynamically, inertially and elastically. The still-air normal modes of the resonance tests, for example, are uncoupled inertially, and elastically; this can be seen from the fact that they appear singly and do not induce one another; but if air forces are brought into play, the picture alters radically. The principle of the mass balancing of control surfaces is to break the inertial coupling between them and the main surface, thus preventing that particular mode of flutter. Indeed it is becoming necessary on high-speed aircraft to over mass balance by some 18 per cent. to overcome the virtual inertia of the air and to provide positive damping.

Flutter calculations are concerned with the determination of the critical speed at the boundary between the stable and unstable motions. Below the critical speed the energy absorbed from the air stream is not enough to overcome the damping actions, and any disturbance subsides with time. Above the critical speed the surplus aerodynamic energy promotes an increasing amplitude, with possibly catastrophic results. At the critical speed, conditions are such that the energy absorbed from the air stream just balances that dissipated by the inertia, elastic and damping forces (both aerodynamic and structural) and the motion is just maintained with constant amplitude. A mathematical solution of the problem is arrived at by assuming that at the critical speed all parts of the structure are executing a simple harmonic motion with a common frequency.

6.2. Simplified physical causation of flutter

Although the physical and mechanical aspects of flutter have been well described by previous authors, and the vibrating aircraft could be dismissed as simply an elastic structure supporting certain masses and acted upon by oscillatory air loads, it might be as well to consider the manner in which energy can be drawn from the air stream in the simple case of flexure-torsion flutter. It will then be easier to deal with the mathematical approach to the problem.

Assume a torsionally rigid wing whose incidence to an air stream can be fixed in value, but which is free to vibrate up and down in pure flexure. Then all chordwise sections will move translationally in a plane perpendicular to the stream. Fig. 11 shows that the effect of upward movements of the wing is to increase the downward angle of incidence and so to produce a downward force in opposition to the upward motion.

For downward motion everything is reversed and so the force still opposes the motion. The result is a stable damped oscillation.

Assume that the wing is now able to twist along its length, and so give the system a second degree of freedom. Further, let it be supposed that the nature of the structure is such that for upward movements a slight increase in upward incidence is obtained due to the torsional vibration. Then, as shown in Fig. 12, the force from the air stream will assist the vertical motion. A slight extension of the argument will show that under certain conditions the system can be made self-running. For example, if further upward motion of the wing can induce the necessary couple to decrease the wing incidence one quarter of a cycle later, this will induce downward force and motion which subsequently lead to an upward incidence and upward motion. That is to say it is necessary for the torsional vibration to lag behind the flexural vibration and be approximately in phase with the vertical velocity. Under these conditions force and motion always act in the same direction, reversing in step and thus positive work is done *by the air stream* throughout the cycle. If this energy is more than the structure can absorb, failure will result.

The reasoning followed in order to arrive at the physical causation of this type of flutter has led to an over-simplification of the problem, and all forms of flutter cannot be thus easily explained away.

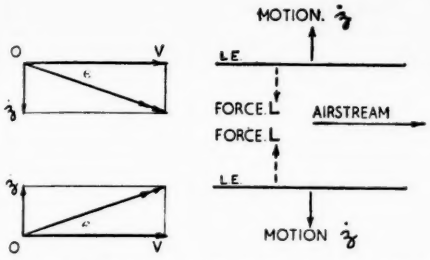


Fig. 11. Damped oscillation of wing single freedom in flexure.

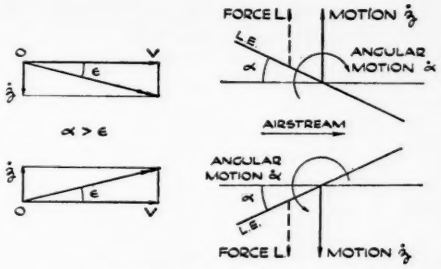


Fig. 12. Sustained oscillation of wing. Two freedoms—flexure and torsion.

6.3. THE "SEMI-RIGID" PRINCIPLE

Another concept usual in flutter work, that of considering the aircraft as a "semi-rigid" structure, is now discussed. The structure is assumed to be able to deform its equilibrium shape only in a limited number of well-defined ways, or to have a certain number of degrees of freedom. Consider a simple cantilever wing. The only large deformations it can have will be in the nature of some mode of flexure *along* the flexural axis and some mode of torsion *about* the flexural axis. The large number of ribs will maintain the chordwise shape of the wing, and the longitudinal rigidity will render spanwise deformations negligible. Thus the behaviour of such a wing can be expressed adequately by the combination of flexural and torsional modes. In this context, the flexural axis may be defined as the locus of those points at which a force may be applied normal to the chord without producing relative twist between adjacent cross sections.

In practice the aircraft structure has infinite freedoms, and when flutter occurs the whole structure will vibrate. Nevertheless certain modes will predominate, depending on the type of flutter in question. In a calculation the difficulty lies in choosing *a priori* just the right degrees of freedom to express the motion adequately in the simplest way possible; that is, the best shape from the smallest possible number of degrees of freedom. This factor is important in reducing the computational labour involved in a calculation, since this increases roughly as the factorial of the number of freedoms employed. The freedom modes chosen "type" the flutter; for example: "aircraft pitch—fuselage flexure—elevator flutter.". This would be a ternary calculation, one with four freedoms a quaternary and so on. With swept-back wings the rigid body freedoms play an essential part in the motion; also, flutter involving control surface freedoms is more likely than that excluding them; further, flutter involving the tail-unit is more likely than that involving the wings, but this last is the most dangerous. These are general statements, and the exception which proves the rule must not be forgotten.

6.4. BASIC BINARY FLUTTER THEORY

Consider the case of two-freedom, or binary, flutter for a wing vibrating in flight and combining two modes in the manner already discussed. At any instant in time every point on the structure will have an acceleration, a velocity, and a displacement from the equilibrium position.

The acceleration acting on each element of mass of the wing produces inertia forces expressible in terms of the kinetic energy. Similarly, "virtual" inertia forces are produced in the adjacent air which is accelerated in sympathy. These are small in relation to the structural inertia, but not negligible.

The velocity is associated with the damping forces. Here the position is reversed, and the aerodynamic damping is large, while the structural damping due to

"solid friction" or hysteresis is, in practice, negligible. This is fortunate as its inclusion greatly complicates the analysis. The aerodynamic forces will have to do positive work in order to overcome the damping and sustain the oscilllation or make it a divergence. If the motion is a subsidence, work is being done on the air stream instead. In other words the air stream is a source, or a sink, of energy.

The displacement is associated with aerodynamic lift and moment forces, and also with a form of potential or stored energy, which, in elastic systems, is termed strain energy.

Consider first the mechanical aspect of the problem. The kinetic energy of a system is half the product of its momentum and velocity, while its inertial reaction is equal to the time rate of change of momentum. Hence, if a simple expression can be obtained for the kinetic energy of a system, the inertia forces will easily be derived from it.

Now express the motion of the vibrating wing, with its two degrees of freedom, in terms of two "generalised co-ordinates" or displacements q_1 and q_2 at the reference section. This means that as the shape of the chosen freedom-modes is known (either from resonance tests or arbitrarily decided), the displacement of any point can be expressed in terms of the displacements q_1 and q_2 at the reference section chosen, the wing tip for example, and similarly for velocities and accelerations.

The velocity of any point on the wing in the direction of vibration can be expressed in terms of the generalised velocities $\dot{q}_1$ and $\dot{q}_2$ as

$$a\dot{q}_1 + b\dot{q}_2 \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where a, b ... are functions of position.

If at that point there is an element of mass m, the kinetic energy of this mass will be

$$\tfrac{1}{2}m(a\dot{q}_1 + b\dot{q}_2)^2 \quad . \quad . \quad . \quad . \quad . \quad (2)$$

Summing all such products over the wing its total kinetic energy T will be obtained in the form

$$T = \tfrac{1}{2}(A_{11}\dot{q}_1^2 + 2A_{12}\dot{q}_1\dot{q}_2 + A_{22}\dot{q}_2^2) \quad . \quad . \quad . \quad (3)$$

where $A_{11} = \Sigma ma^2$, $A_{12} = \Sigma mab$, $A_{22} = \Sigma mb^2$.

Differentiating the kinetic energy with respect to $\dot{q}_1$ gives the net momentum in the "q_1" mode, and hence

$$\frac{\partial T}{\partial \dot{q}_1} = A_{11}\dot{q}_1 + A_{12}\dot{q}_2 \quad . \quad . \quad . \quad . \quad . \quad (4)$$

Similarly

$$\frac{\partial T}{\partial \dot{q}_2} = A_{12}\dot{q}_1 + A_{22}\dot{q}_2 \quad . \quad . \quad . \quad . \quad . \quad (4a)$$

for the "q_2" mode.

The rate of change of this momentum provides the inertia force in the mode. This is written as

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{q}_1}\right) = A_{11}\ddot{q}_1 + A_{12}\ddot{q}_2 \quad . \quad . \quad . \quad . \quad . \quad (5)$$

for the q_1 direction.

Similarly

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{q}_2}\right) = A_{12}\ddot{q}_1 + A_{22}\ddot{q}_2 \quad . \quad . \quad . \quad . \quad . \quad (5a)$$

for the q_2 direction.

The potential or strain energy of the elastic structure of the wing is now

considered. Assuming small displacements, in general the elastic restraint to a displacement q will be an elastic force F, where

$$F_1 = -E_{11} q_1 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

and similarly

$$F_2 = -E_{22} q_2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6a)$$

E_{11} and E_{22} are dynamic stiffness constants appropriate to each mode. The negative sign indicates that the elastic force acts in the opposite direction to the displacement. If U is the potential energy,

$$F_1 = -\frac{\partial U}{\partial q_1} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

and

$$F_2 = -\frac{\partial U}{\partial q_2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7a)$$

Hence it follows at once that the expression for the potential energy of the wing is

$$U = \tfrac{1}{2}(E_{11} q_1^2 + E_{22} q_2^2) \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

It should be noted that the potential energy is positive and is equal to the work done by the *external* forces causing the displacement, whereas the *internal* elastic forces do negative work.

The term $2E_{12} q_1 q_2$ which exists in the general case has been omitted. The reason is that

$$E_{12} = 0 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

for elastically uncoupled modes. This condition can be satisfied by using normal modes, which are uncoupled since they appear individually, from a resonance test, or by choosing arbitrary modes in flexure and torsion, for example, with respect to the flexural axis. By definition, the modes are then uncoupled with respect to this axis, *i.e.* neither one tends to induce the other.

Differentiating (8) or equating (6) and (7) gives the external force causing the elastic displacement in the q_1 direction as

$$\frac{\partial U}{\partial q_1} = E_{11} q_1 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (10)$$

Similarly

$$\frac{\partial U}{\partial q_2} = E_{22} q_2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (10a)$$

The aerodynamic forces are expressed in terms of derivatives. These are the rates of change of lift or moment with respect to the acceleration, velocity or displacement, of the particular motion concerned relative to the equilibrium position. It is usual to relate the displacement of the wing to the leading edge so that at any instant the position of any point on the wing can be obtained from the leading edge displacement z and the incidence α. The influence on the lift force and aerodynamic moment for slight changes in z, α, $\dot{z}$, $\dot{\alpha}$, $\ddot{z}$ and $\ddot{\alpha}$ can be obtained from existing tables of leading edge derivatives, giving rise to the virtual inertia, aerodynamic damping and aerodynamic stiffness terms. The calculation of these derivatives is beyond the scope of this paper, but the assumptions made in their calculation will be discussed later. Incidentally a wing-aileron-tab system involves the calculation of 48 derivatives, in themselves involved functions.

The leading edge displacement may now be written as

$$z = eq_1 + hq_2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

and the incidence

$$\alpha = jq_1 + kq_2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (12)$$

where e, h, j and k depend upon the position on the leading edge of the point in question.

The aerodynamic work function is obtained in the form

$$\delta W = \delta L\, \delta z + \delta M\, \delta \alpha \quad . \quad . \quad . \quad . \quad . \quad (13)$$

(Note: δL and δM are derived from consideration of an elementary wing strip, not as increments of L and M).

Therefore

$$\delta W = D_1 q_1\, \delta q_1 + D_2 q_1\, \delta q_2 + D_3 q_2\, \delta q_1 + D_4 q_2\, \delta q_2 \quad . \quad . \quad . \quad (14)$$

where D_1, D_2, D_3 and D_4 are differential operators of the form

$$D = \lambda \frac{d^2}{dt^2} + \mu \frac{d}{dt} + \eta \quad . \quad . \quad . \quad . \quad . \quad (15)$$

so that

$$D_1 q_1 = \lambda_1 \ddot{q}_1 + \mu_1 \dot{q}_1 + \eta_1 q_1 \quad . \quad . \quad . \quad . \quad (16)$$

and λ, μ and η are constants depending on the shape of the deformation and on the derivatives. It follows that

$$\frac{\partial W}{\partial q_1} = D_1 q_1 + D_3 q_2 \quad . \quad . \quad . \quad . \quad . \quad (17)$$

This is the generalised aerodynamic force Q_1 in the q_1 mode.

Similarly

$$Q_2 = \frac{\partial W}{\partial q_2} = D_2 q_1 + D_4 q_2 \quad . \quad . \quad . \quad . \quad . \quad (17a)$$

in the q_2 mode.

Thus all that is required in order to evaluate D_1, D_2, D_3, and D_4, is a knowledge of the shape of the vibrations or modes chosen and the values of the derivatives obtained from standard tables.

It now remains to collect together the forces that have been calculated. Remembering that action and reaction are equal and opposite it may be stated that the aerodynamic action on the wing is equal and opposite to the inertial and elastic reaction. Thus:—

Inertia Force + Elastic Force = Aerodynamic Force.

In general terms this has the rather formidable expression

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{q}_r}\right) + \frac{\partial U}{\partial q_r} = Q_r = \frac{\partial W}{\partial q_r} \quad . \quad . \quad . \quad . \quad (18)$$

for all freedoms, where $r = 1, 2, 3 \ldots n$ freedoms (in a binary $r = 1, 2$). These are the Lagrangian equations, corresponding to each freedom for each value of r. Since these equations are second-order differential equations, it can be seen that it pays to keep the number of freedoms as small as possible. Assuming the vibration to be a simple harmonic motion, the solution will be of the form

$$q = q_0 e^{i\omega t} \quad . \quad . \quad . \quad . \quad . \quad . \quad (19)$$

where

$$\omega = 2\pi f \quad . \quad . \quad . \quad . \quad . \quad . \quad (19a)$$

and f is the flutter frequency.

The detail of the solution of the resulting simultaneous linear homogenous equations with complex coefficients is standard practice. There are certain devices particular to this problem, however, which are worth noticing.

The first artifice is to employ a frequency parameter

$$\nu = \frac{\omega c}{V} \quad . \quad . \quad . \quad . \quad . \quad . \quad (20)$$

Hence it follows that

$$\ddot{q} = -\omega^2 q_0 e^{i\omega t} = -\nu^2 \frac{V^2}{c^2} q_0 e^{i\omega t} \quad . \quad . \quad . \quad . \quad (21)$$

and the inertia force becomes

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{q}_r}\right) = -\nu^2 \frac{V^2}{c^2} (\Sigma_s A_{rs} q_{s0}) e^{i\omega t} \quad . \quad . \quad . \quad . \quad (22)$$

where $r=1, 2, \ldots n$ and $s=1, 2, \ldots n$ (in a binary $r=1, 2$; $s=1, 2$), and Σ_s denotes the sum of all such terms for all values of s.

The aerodynamic forces are of the form

$$Q_r = \frac{\partial W}{\partial q_r} = \rho V^2 c^2 \frac{\partial}{\partial q_{r0}} (L, M) e^{i\omega t} \quad . \quad . \quad . \quad . \quad (23)$$

where ρ is the air density and $r=1, 2, \ldots . n$ ($r=1, 2$ in a binary).

The second artifice is to leave E_{11} and E_{22} (stiffness coefficients) explicitly in the equation. On dividing out by $e^{i\omega t}$:—

$$-\frac{\nu^2}{\rho c^3} \Sigma_s A_{rs} q_{s0} + \frac{E_{rr}}{\rho V^2 c^3} q_{r0} = \frac{1}{c} \frac{\partial}{\partial q_r} (L, M) \quad . \quad . \quad . \quad (24)$$

It is usual to write

$$\frac{E_{11}}{\rho V^2 c^3} = X \quad . \quad . \quad . \quad . \quad . \quad . \quad (25)$$

and

$$\frac{E_{22}}{\rho V^2 c^3} = Y \quad . \quad . \quad . \quad . \quad . \quad . \quad (25a)$$

In the solution of the problem the ratio X to Y in terms of Y, say, is obtained for various values of ν. In the evaluation of the kinetic energy the general form was

$$T = \tfrac{1}{2} [A_{11}\dot{q}_1^2 + A_{22}\dot{q}_2^2 + (2 A_{12}\dot{q}_1 \dot{q}_2)] \quad . \quad . \quad . \quad (26)$$

as calculated for the chosen modes. If the modes chosen are normal modes from a resonance test, then there is no inertial coupling between them and A_{12} is zero. The quantity in the round brackets then vanishes, and if substitution be made in a Langrangian equation representing the resonance conditions for still air, *i.e.* velocity $V=0$ and aerodynamic work function $Q_r=0$, it can be shown that

$$E_{11} = \omega_1^2 A_{11} \quad . \quad . \quad . \quad . \quad . \quad . \quad (27)$$

where ω_1 is the resonance circular frequency associated with mode q_1. Similarly for E_{22}. Since A_{11} and A_{22} are numerically obtained, E_{11}, E_{22} and the ratio E_{11} to E_{22} are also obtained. This is the same as the ratio X to Y mentioned previously. The value of ν giving the right value of X to Y is chosen, and hence Y. Knowing E_{22} the speed follows immediately for any altitude. Substitution in the frequency parameter then gives the flutter frequency. *These are the critical values for V and f for which the motion is just sustained.*

If no resonance tests have been performed and arbitrary modes are used, the term $2 A_{12} \dot{q}_1 \dot{q}_2$ in (26) must be retained as it may have a considerable magnitude. Further, the values of E_{11} and E_{22} have to be evaluated from static stiffness tests in which a static loading reproduces the shape of the modes chosen, the conditions being such as to uncouple the modes elastically, as explained for equation (9), and to make $E_{12}=0$. The solution then follows as with normal modes. It must be remembered that stiffness tests with single loads give a low value for the equivalent dynamic stiffness.

6.5. Calculation Procedure

In a flutter calculation the first step is to determine from drawings the geometry of the structure, and from the Weights Department the mass distribution. If it

is intended to use normal modes from resonance tests, care must be taken to see that the mass distribution used in the calculation corresponds to that for the resonance tests (or normal mode calculations); otherwise A_{12} will not be zero or nearly so.

The next step is to analyse the shape of the chosen modes of vibration. As previously explained the shape of the wing in each mode is defined as the displacement of its leading edge z and its angle of incidence α in terms of a generalised co-ordinate q. Hence along the leading edge, for mode q_1

$$z_1 = f_1(y)\, q_1 \quad . \quad . \quad . \quad . \quad . \quad . \quad (28)$$

and similarly for mode q_2. y is the spanwise co-ordinate and $f(y)$ is the displacement function such that when $y = s$ (the position of the reference chord) then

$$f(s) = 1 \quad . \quad . \quad . \quad . \quad . \quad . \quad (29)$$

Similarly for the incidence in mode q_1

$$\alpha_1 = F_1(y)\, q_1 \quad . \quad . \quad . \quad . \quad . \quad . \quad (30)$$

where the torsional displacement function $F(s) = 1$ at the reference chord (usually the wing tip). Similarly for mode q_2.

If resonance test modes are used, the displacement functions $f(y)$ and $F(y)$ will not be known. They may each be represented, however, by a polynomial of degree $(m-1)$ where m is the number of test points at which the amplitude was measured. If these are positioned $y_1, y_2, y_3, \ldots . s$ along the span, then

$$p_1 y_r^{m-1} + p_2 y_r^{m-2} \ldots . \; p_{m-1} y_r + p_m = K_r = \frac{z_r}{z_s} \quad . \quad . \quad . \quad (31)$$

where K_r = ratio of amplitude at y_r to amplitude at s. Thus there will be m simultaneous equations to solve for the m coefficients, $p_1, p_2 \ldots . p_m$.

If $m > 4$ however, it is much more convenient to draw a graph of the displacement and so obtain values at the intermediate points. Whichever way is chosen, it will be necessary to evaluate in a binary

$$z = f_1 q_1 + f_2 q_2 \quad . \quad . \quad . \quad . \quad . \quad . \quad (32)$$

and

$$\alpha = F_1 q_1 + F_2 q_2 \quad . \quad . \quad . \quad . \quad . \quad (33)$$

for all sub-divisions of the wing which it may be thought necessary to take in order to evaluate the kinetic energy and the aerodynamic work function to the desired accuracy. Except in the most simple cases it is not easy to obtain these expressions by integration, and numerical approximation by summation is much more convenient for the large number of integrals required. In all cases it is usual to calculate the value of A_{12}. The ratio of A_{12}^2 to $A_{11}\, A_{22}$ should not be more than 10 per cent. if the normal modes have been correctly determined. The ratio is usually much smaller than this, sometimes less than one per cent. It forms a useful check on the calculations and resonance test modes.

The critical speed or flutter speed, for wings for example, is often expressed as a function of the torsional stiffness for a given flexural/torsional stiffness ratio. With control surface flutter, however, the mass balance weight is usually left as the variable parameter.

Figure 13 shows a typical flutter boundary for elevator flutter. Flutter speed has been plotted against elevator mass balance weight. The boundary separates the stable and unstable regions, and there is another branch of the curve well to the right (not shown). Off the top of the diagram is the wing flutter boundary. The mass balance fitted is well within the safe region. This diagram also illustrates the fact that in this instance the binary calculation was as good as the quaternary, and emphasises the saving in labour obtained from the correct initial choice of modes.

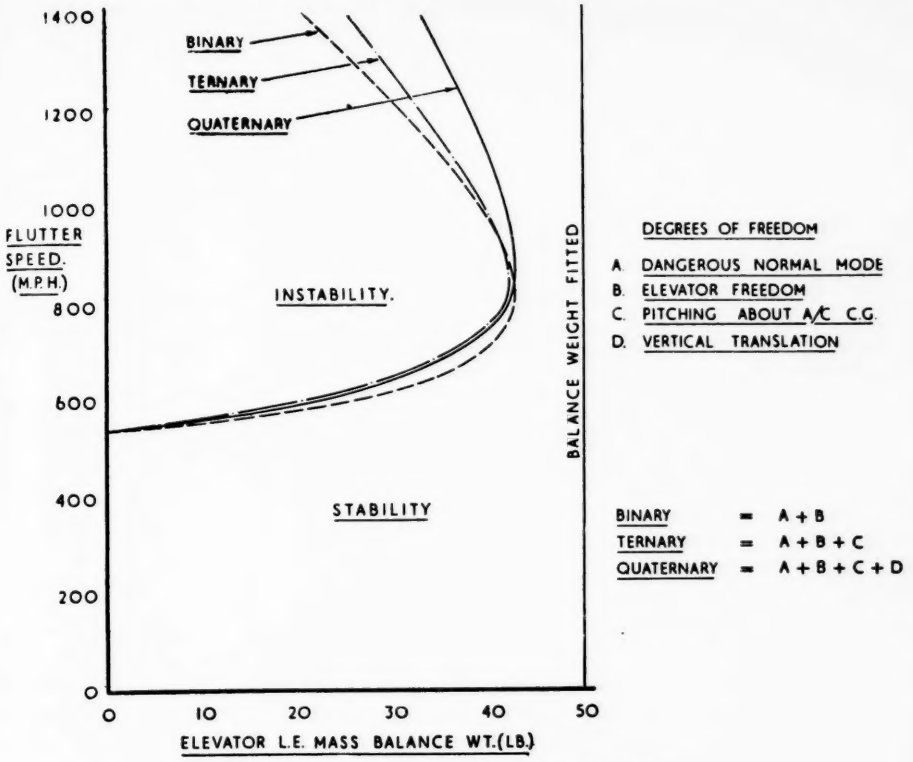


Fig. 13. Typical flutter boundary Elevator flutter.

It is an interesting fact that flutter is unlikely to include modes of a resonant frequency much greater than 30 c.p.s. Now, it has been shown at the National Physical Laboratory and by Hawker Aircraft Ltd. that the greatest value of the frequency parameter for which energy may be extracted from the air is 1.7 (based on theoretical derivatives). Assuming an aircraft of 7 ft. chord and a flutter speed of 1,000 m.p.h. and substituting in $\nu = \omega c/V = 2\pi fc/V$ a frequency of $f \simeq 50$ c.p.s. is obtained. Hence at a flutter speed of 1,000 m.p.h. the maximum possible flutter frequency would be about 50 c.p.s. But for unswept wings it is known from experience that ν is usually between 0.8 and 0.6 (frequencies $\simeq 25$ c.p.s. and 17 c.p.s.) while for swept wings ν lies between 0.6 and 0.3 (say 17 c.p.s. to 9 c.p.s.). Thus the emphasis is on the lower frequency range.

The calculations are usually started in ft., slug., sec., units and later corrected to non-dimensional coefficients. The calculations are usually performed on automatic calculating machines to six significant figures for a ternary and seven for a quaternary.

7. CONCLUSION

Until new criteria are evolved, or experience accumulates, which is unlikely because of the rapid evolution of design, the designer will be hard pressed to replace the cumbersome methods of resonance testing and flutter calculations in order to clear an aircraft for high-speed flight.

On a new type of aircraft the logical sequence of events would be calculation of normal modes plus flutter calculations in the design stage, followed by ground resonance tests on the prototype aircraft and check flutter calculations. Coupled with this would be careful flight testing with vibrograph recorders. Maximum performance would be restricted until a satisfactory calculated flutter speed had been obtained. (The flutter speed would have to be some 20 per cent. greater than the diving speed for Mach numbers up to 0.6. With $M \geqslant 0.8$ the margin would be increased to 30 per cent.).

The resonance testing equipment should be able to measure phase angles to within some 3° instead of the present 30° and multiple fixed pick-ups and switch gear would cut down testing time enormously. The interpretation of the tests is still in its infancy.

The basis of flutter theory was laid down in 1928 and with developments has proved an adequate instrument. Without it the all-important mass balancing of control surfaces would never have been fully understood. The electronic simulator will no doubt cut down the forest of freedoms which surrounds us, saving both time and labour, but the results of flutter calculations stand or fall by the accuracy of the flutter derivatives used. Complete sets of theoretical derivatives exist, based on thin aerofoils in an irrotational incompressible fluid. The main surface derivatives are also available including compressibility effects up to $M=0.7$ to 0.8 and for supersonic flight, but in all cases the results are for large aspect ratios. What is required, and urgently, are the derivatives for the range $M=0.8$ to 1.2 and for low aspect ratios. At present next to nothing is known of the derivatives in the transonic region as they have proved so far intractable to calculation; faith must be pinned therefore on experiments now in hand. The only regret is that the results so badly needed are not available now. This should suffice to emphasise that the subject is still in full evolution and cries aloud for more experimental and theoretical research.

Acknowledgments

The author thanks Mr. Sidney Camm, Director and Chief Designer, Hawker Aircraft Limited, for permission to publish this paper. He also thanks those of his colleagues who assisted him by providing various data and constructive criticism.

Any opinions expressed in the paper are the author's own.

REVIEWS

The following are reviewed:—

Aerodynamics of Supersonic Flight
Physics of Lubrication
Mechanics Applied to Vibrations and Balancing

AERODYNAMICS OF SUPERSONIC FLIGHT. Alan Pope. Pitmans Aeronautical Publications. New York, 1951. 184 pp. Illustrated. Appendix. 25s. net.

This book is based on a one-term introductory course on supersonic flow given by the author to undergraduate students at the Georgia Institute of Technology. A preliminary knowledge of elementary aerodynamics and of the differential and integral calculus is assumed. Following a short introductory chapter, there are chapters on steady flow in one, two and three dimensions, and on supersonic wind tunnels and other experimental methods. Some of the techniques used for making observations with these methods are also described, and there are short sections on propulsion systems for supersonic flight and on the performance of a supersonic aeroplane. In the chapter on three-dimensional flow, the detailed analysis is confined to wings of rectangular and trapezoidal plan form; the performance of swept and delta wings and the flow past bodies of revolution are discussed only briefly. Numerous worked examples and problems are included, and there is a valuable list of about forty American supersonic tunnels. Tables and charts relating to Prandtl-Meyer expansions and oblique shock waves, and to the flow past aerofoils and cones are included. The references are mainly to American work, but some British papers are also mentioned. An Appendix gives the properties of the standard atmosphere up to an altitude of 80,000 feet.

The field which is covered is so wide that the treatment is necessarily superficial in places, but most of the major features of supersonic flow seem to be brought out. The choice of subjects for detailed discussion is sometimes questionable; there is, for example, a lengthy account of the Busemann biplane but comparatively little discussion of boundary-layer phenomena. The author has attempted the difficult task of dealing with his subject without detailed reference to the underlying thermodynamics, and this results for example in the omission of a discussion of the second law of thermodynamics in relation to the alternative solutions of the shock-wave equations.

There are some errors and several statements which may mislead the reader,* but on the whole the book can be recommended to those requiring a broad and simply-worded introduction to the subject without complicated mathematics or a detailed description of the basic physical principles.

* A reader has also commented on this book as follows:—
"You might be interested in a mistake which I found on page 70, Fig. 4:10, which shows the shock wave from a supersonic wing intersecting and cancelling out. I believe I am right in saying that Lighthill has shown that both the shock waves will set themselves parallel between another at the Mach angle and do not cut out by the simple procedure outlined in Pope's book.
"I also noticed on page 110, Fig. 6:6 that the dryer and compressor would normally be interchanged in this arrangement of wind tunnel, as it would result in much better economy of first cost, and of operation."

PHYSICS OF LUBRICATION (A Symposium held jointly by the British Rheologist's Club and the Manchester and District Branch of the Institute of Physics). The Institute of Physics. London, 1951. 96 pp. Illustrated. Index. 15s. net.

This is an excellent collection of papers covering a wide range of aspects of lubrication. The controversial nature of much of the subject matter is evident, but it is important that this factor should be properly weighed in determining the future course of research.

It is clear that in some cases, at least, research workers still fail to understand the necessity for accurate definition on the one hand of the surface used and its cleanliness and, on the other, the composition of the lubricant. It cannot be too strongly urged that the term castor oil (B.P.) does not define a lubricant in any way appropriate to scientific study.

Part I consists of four papers covering fluid lubrication and rheology of lubricants. Professor Christopherson reviews completely the basic theory which can be used for bearing design and for defining the properties of a lubricating fluid. It is felt that more might have

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been made in this paper of the influence of compressibility and the related marked rise in viscosity under high pressures. Modern theories of " running in " are reviewed.

Dr. Mardles' paper on the rheology of lubricant films indicates the complex nature of these films at high pressure. In the discussion on this paper, owing to an error of reporting, castor oil and fluoro-carbon are referred to as " other hydro-carbon oils."

The paper by Dr. Ward, Dr. Neale and Mr. Bilton reports work on the viscosity of lubricating oils at high rates of shear, using mineral oil-polymer blends of the improved viscosity index type. It would have been of great value to have seen the effect of shear on the additive, a factor of great importance.

Mr. Moss's paper on the lubrication of cotton is interesting and valuable. Non-metallic friction is a subject of great interest and deserves wider study than it receives at present.

Part II of this symposium covers boundary lubrication. A summary of this field is provided in Dr. Clayton's paper, while Professor Finch surveys present theories of formation of the boundary layer.

Barwell and Milne have studied the effect of solid lubricants on friction and wear. It is remarkable that paraffin wax should be an excellent lubricant under conditions of light load and low speed. In a second paper they emphasise the important effect of the rheology of soaps and surface layers. It would be interesting to see the effect on the higher melting alkali metal soaps.

The potential value of the technique using radioactive tracers is demonstrated in Dr. Moore's paper.

MECHANICS APPLIED TO VIBRATIONS AND BALANCING (2nd Edition). D. Laugharne Thornton. Chapman & Hall. London, 1951. 584 pp. 206 figures. 50s. net.

The first edition of this book appeared in 1939, and the only changes in the Second Edition, apart from minor corrections, consist in the addition of an extra chapter on "Dynamic Loading of Structures," and a rewritten last chapter entitled " General Survey."

A word for those not familiar with the book in its original form may not be out of place before discussing these changes. It is largely based on the author's experience as a consulting engineer, which accounts for a certain lack of that logical sequence which one would expect in a book based on lecture notes. Thus the first two chapters deal respectively with the balancing of engines and locomotives and it is not until Chapter III that the author settles down to a discussion of the General Theory of Vibrations, although curiously enough he has already taken occasion to tuck a major item in that theory—Lagrange's Equations—into Chapter I.

The general impression is that on matters with which the author has not had practical contact he is sound without being illuminating, but that on matters on which he has actually done work—and they are not a few—he is interesting and authoritative. Thus, whereas his long Chapter V on " Beams and Plates " and their natural frequencies and modes contains little that is not equally well presented in various standard text books, he has a useful and instructive Chapter IV on the " Propagation of Stress in Elastic Materials." The examples given in this chapter cover the problems of stress transmission through reinforced concrete, earth waves due to earthquakes, water hammer, and pressure waves in hydraulic fluids. The remaining chapter deals with rotating shafts and discs and is concerned with methods of estimating their natural frequencies and whirling speeds. Turbine wheels and blades and gyroscopic action are also discussed in this chapter.

The new chapter of some thirty (out of a total of 580) pages on the " Dynamic loading of Structures " is concerned with the behaviour of structures under suddenly applied loads such as impacts, and is frankly disappointing. It has little of interest to aeronautical engineers because the author has chosen to interpret the word " dynamic " in a very limited sense. In the aeronautical world " dynamic " loading includes all rates of loading that are rapid enough to induce inertia forces comparable with the forces associated with a purely static response to the same applied load. In this new chapter, however, the author has in mind a much more rapid rate of loading, in which the rate of propagation of the stress pulse becomes an important factor in the value of the resultant stress. He concerns himself with such matters as the velocity of propagation of stress waves, the damping of such waves, and their reflection —or partial reflection—at sections of discontinuity in the medium. There is here a welcome section on flexural stress waves, a subject much less commonly understood than are torsional or extensional stress waves, and much more frequently omitted from text books.

The conventional method of treating transient loads by finding the response of the structure in each normal mode separately is not mentioned, and the author is clearly not aware of the recently introduced method of segregating the inertia from the elastic forces, which so conspicuously increases the convenience and accuracy of the conventional approach.

Taken as a whole the book is likely to be of most value as a work of reference for the practising engineer, who will find the numerous worked examples of considerable help, and who can easily overlook a certain discursiveness and lack of balance as between primary and secondary matters that do not help a student. The alleged dual purpose of catering for engineers and physicists—never an easy task—can hardly be said to have been achieved here.

In a cursory reading the writer found only one error that cannot be regarded as minor—an error, by the way, that shows the danger of a too facile use of analogy. It refers to the natural period of an unloaded coil spring under axial vibration. This, for a spring fixed at one end, is equal to the time taken by the stress wave to travel the length of the spring four times. As the velocity of a torsional-shear pulse in a straight shaft is $\sqrt{(G/\rho)}$, where G is the Shear Modulus and ρ the density of the material, the author argues that the period must, since the spring is merely a coiled shaft under torque, be $4 \times 2\pi n R/\sqrt{(G/\rho)}$ where n is the number of coils and R the coil radius. This is wrong because the velocity $\sqrt{(G/\rho)}$ is based on the assumption that the relevant inertia is the polar moment of inertia of the wire. This is not so, as the relevant inertia is that due to bodily motion of the coils in the axial direction. The true period is $16\pi n R^2/[r\sqrt{(G/\rho)}]$ and is therefore $2R/r$ times that given by the author. The effect of the polar moment of inertia of the wire, although present, is negligible. The error is unfortunate in that the same false analogy vitiates the subsequent somewhat extensive discussion of tapered coil springs.

CORRESPONDENCE

" FELLOWSHIP OF THE AIR "

May I make a modest riposte to what I must regard as unfair comment in the review (December 1951 JOURNAL, p. 807) of " Fellowship of the Air " which book it was my privilege to write for the Royal Aero Club.

The first, and indeed paramount, point which your reviewer fails to understand is that Harold Perrin was not a member of the Royal Aero Club. He must, perforce and by favour only, take his turn in the queue for photographic inclusion, and, by the same token, many a Member who is not included photographically could object to his inclusion at all.

But, in agreement that Harold Perrin was a live factor in the Club, what sort of photograph does your reviewer expect? Would he like to see Perrin of the period 1905-15—there are several lively photographs which present him as next brother to a fishmonger; for the fashions have changed considerably, and a photo of Perrin in a straw hat would not, to modern readership, do him justice. However, I personally did not choose any of the photographs, or even write the captions.

Now for the admission that my work has flesh and bones but no blood. Let this go on record: that the original MS (which has been presented to the Club for use by some future historian) runs to 118,000 words up to 1945. A post-war section condensed five hectic years into a mere 8,000 words. But the grand total of 126,000 words was, because of paper supply and production difficulties, cut to only 84,000 words. Much of the " blood " dripped away here; but it is vain to think that Sir Francis McClean, Mr. O. Short or Lord Brabazon could have helped me more or done more to make this a fair presentation of a story which, I am the first to admit, could easily run to several Volumes.

As for the suggestion that venerable Members should let down " what hair they have left," that way madness lies. It does not seem to occur to your reviewer that Mr. A holds diametrically opposing views to Mr. B, has held them all his life, and that the antipathy is reciprocated in full. To secure *fact* from people who are violently biased is fundamentally impossible, unsatisfactory to narrative, and manifestly on one side or the other a blatant distortion of history.

If your reviewer will point to a mis-statement of fact, then that is something a genuine historian would like to know and to correct as best possible. If he can only vaguely assert that what he believes to be fact—material fact as that—has been omitted, then that calls for examination and the production of probably conflicting evidence. What one feels he really seeks is a gossip book.

However your reviewer is himself careful to point out that a gossip book is open to attack for libel, and that course would be most unhappy for the dignity and prestige of the Royal Aero Club.

To clear the air completely, let it also go on record that the MS was read in detail by Lord Brabazon, Sir Francis McClean, Major Mayo, Colonel Preston and Sir Roderick Carr. All of them made valuable suggestions. Thus it seems that the only course now left open, after this body of expert opinion, is for your reviewer to write or promote the gossip book which, it appears, alone will satisfy him—there is nothing to stop him so doing.

B. J. HURREN.

ROYAL AERO CLUB, W.1.

(No comment—The Reviewer.)

ADDITIONS TO THE LIBRARY

The following have been added to the Library. Books and papers marked with an asterisk may not be taken out on loan; the titles of pamphlets are printed in italics.

American Society for Testing Materials. Materials at Elevated Temperatures. A.S.T.M. 1951.

Farrington, G. H. Fundamentals of Automatic Control. Chapman & Hall. 1951.

*Hrones, J. A. and G. L. Nelson. Analysis of the Four Bar Linkage. Chapman & Hall. 1951.

Ley, Willy. Rockets, Missiles and Space Travel. (2nd Edition.) Chapman & Hall. 1951.

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*Reuss, K. F. Jahrbuch der Luftfahrt 1951/2. Pohl & Company. 1951.

*U.S. National Bureau of Standards. Bibliography of Books and Published Reports on Gas Turbines. U.S.G.P.O. 1951.

*Whitaker 1952.

Aeronautical Research Council. Reports and Memoranda.

2355—*Tests on a "Lighthill" nose-suction aerofoil in the N.P.L. 4-ft. No. 2 wind tunnel. F. Cheers, W. G. Raymer and Ola Douglas.*

2458—*Tests on yawed aerofoils in the 20 x 8-in. high speed tunnel. J. A. Beavan and Miss N. Bumstead.*

2463—*An investigation into the effect of forced and natural afterbody ventilation on the hydrodynamic characteristics of a small flying boat (Saro 37) with a 1:15 fairing over the main step. J. A. Hamilton.*

2482—*Some observations on sharp-nosed profiles at supersonic speed. J. Valensi and F. W. Pruden.*

2512—*The ideal drag due to a shock wave. Parts I and II. C. N. H. Lock.*

2537—*An approximate solution of two flat plate boundary-layer problems. E. J. Watson and J. H. Preston.*

2607—*Contra-flow turbo-compressor tests. A. D. Baxter and C. W. R. Smith.*

Aeronautical Research Laboratories, Australia. Reports.

A.77—*A review of leading edge high lift devices. K. D. Thomson.*

SM.172—*The buckling of uniformly compressed parallelogram plates having all edges clamped. J. Guest.*

SM.173—*Influence of shape on the weight of fuselage rings in pressure cabins. J. Solvey.*

Notes.

Aerodynamics 105—*Wind tunnel tests of a 3ft.-chord two-dimensional Glas II aerofoil for comparison with flight tests. P. B. Atkins and T. S. Keeble.*

Flight 17—*Wing leading edge contamination by insects. P. B. Atkins.*

Structures and Materials 189—*Interim note on repeated load testing of "Mustang" P-51D wings. C. A. Patching.*

National Aeronautical Establishment, Canada. Notes.

No. 7—*The rate of evaporation of a kerosine spray. W. Sacks.*

Reports.

LR-3—*Orifice-type ice detector; preliminary icing tunnel tests of functioning as ice detector, rate-of-icing meter, and icing severity meter. D. Fraser.*

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No. 252—*Contribution a l'étude des couches limites turbulentes avec gradient de pression. R. Michel.*

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